A Novel Methodology for Enhancing Flood Risk Communication: The Nines of Safety

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Abstract

Flood risk communication helps people plan for and recover from disasters, especially in flood-prone areas. The Nines of Safety (NoS) concept described in this study provides a new perspective for flood risk communication and assessment. The NoS method can help analyze flood risk comprehensively, and support decision-makers and the public understand their vulnerability at various conditions. This novel approach considers physical parameters, socioeconomic factors, and demographics to assess flood risk. The analysis demonstrates that water characteristics are crucial to determining safety. The socioeconomic parameters deal with how income, age, and population density affect flooding risk. The analysis shows how these factors affect the Nines of Safety scale. These variations highlight the importance of a community-specific risk communication strategy. Explaining the complexity of flood risk assessment with this novel method makes it more accessible. Given its quantitative and qualitative effects, this strategy could empower communities to make sensible decisions and adapt to changing flood scenarios. The Nines of Safety concept can help communities better understand their risk. Information on vulnerable individuals and land use can help understand how different factors affect flood risk profiles. This study discusses how the NoS technique can transform flood risk perceptions and strengthen communities. By integrating this new strategy into risk management, stakeholders may tailor their responses to each community, making them more robust to flooding.

Keywords: flood risk, risk communication, Nines of Safety, flood warning, risk perception

1. Introduction

Floods, as recurring natural disasters, inflict profound devastation upon communities worldwide, manifesting as substantial damage to infrastructure, loss of lives, and economic turmoil (Mauch & Pfister, 2009; Mount et al., 2019). It is one of the most devastating natural disasters, causing immense loss of life, property damage, and disruptions to communities and economies worldwide (Mileti, 1999; Alabbad et al., 2023). With the increasing frequency and intensity of extreme weather events attributed to climate change (Nourani et al., 2023), the risk of floods is growing, making effective flood risk communication a critical component of disaster preparedness and response strategies (Lieske et al., 2014; Yildirim et al., 2022). In navigating the complex terrain of flood mitigation, effective flood risk communication emerges as an indispensable tool (Cole & Murphy, 2014).

It transcends the mere transmission of meteorological data (Sit et al., 2023) and flood forecasts (Li and Demir, 2023; Sit et al., 2021), embracing a holistic approach that integrates diverse physical and socioeconomic indicators to comprehensively evaluate and communicate flood vulnerability (Alexander, 2018). Effective flood risk communication involves disseminating timely and accurate information to vulnerable communities (Alabbad and Demir, 2022), enabling them to understand the risks they face, take necessary precautions, and make informed decisions during flood events (Perera et al., 2020). However, traditional flood risk communication methods, such as public service announcements, brochures, and workshops, have shown limitations in reaching all segments of the population, particularly in marginalized and hard-to-reach communities (Thorup-Binger & Charania, 2019).

At the heart of this multidimensional framework lies the nines of reliability concept, devised initially within the aviation industry to assess risk and preparedness (Smith, 1989). Its simplicity and adaptability make it an ideal candidate for enhancing flood risk communication by offering a structured means of conveying intricate information to experts and the public. In flood risk communication, conveying the likelihood of avoiding highly undesirable outcomes, such as loss of life, property damage, or environmental harm, demands a transparent and standardized risk assessment measure (Sayers et al., 2013). Percentages, commonly used to quantify probabilities in various contexts, can pose challenges in interpretation, particularly for those without extensive mathematical training. The perceived significance of a percentage often depends on the specific context in which it is employed. For instance, in electoral politics, a margin of 51% to 49% may be considered close, while in healthcare, an operation with a 51% chance of success is viewed as highly risky.

To address these challenges and facilitate transparent risk communication within the realm of flood vulnerability, we introduce the “Nines of Safety” concept. Originally developed as a unit of measurement for availability or purity across diverse fields, this concept offers a versatile means of quantifying safety and risk. Informally, “nines” measures the consecutive appearances of the digit 9 in the probability of avoiding an adverse outcome. For instance, a 90% probability of success is equivalent to one “Nine of Safety”. In comparison, a 99% probability corresponds to two Nines of Safety, signifying a higher confidence level in avoiding a negative outcome.

This research aims to elevate the efficacy of flood risk communication by harmonizing a spectrum of physical and socioeconomic indicators (Xiang and Demir, 2022) within the Nines of Safety framework. To this end, we have delineated four primary objectives: firstly, to meticulously identify and scrutinize pivotal physical indicators—such as elevation, soil type, drainage density, land use type, and slope—that substantially contribute to flood vulnerability. Secondly, to delve into the intricate interplay of socioeconomic indicators—encompassing income levels, population density, age distribution, and gender composition—in shaping flood vulnerability within communities. Thirdly, to construct a rigorous and all-encompassing methodology that seamlessly integrates these multifaceted indicators into the Nines of Safety framework, facilitating a comprehensive assessment of flood vulnerability. Finally, to translate these assessments into tangible visuals, effectively mapping flood vulnerability levels onto the Nines of Safety scale will serve as a potent tool to convey the complexities of flood vulnerability to stakeholders, from policymakers to the public.

This research adopts an interdisciplinary approach, synthesizing insights from geography, hydrology, sociology, and communication to bring the proposed methodology to life. We focus on a specific geographic area to ground our study in practicality, as detailed in subsequent sections. Our research strategy employs a comprehensive blend of data collection, rigorous analysis, and the development of visualization tools to communicate vulnerability levels effectively.

This research aspires to pioneer flood risk communication, ushering in integrating physical and socioeconomic indicators into the Nines of Safety framework. Through this endeavor, we aim to empower communities and stakeholders with a profound, actionable comprehension of flood vulnerability, enabling informed decisions and the development of resilient flood risk management strategies. The subsequent chapters delve into the intricate tapestry of our research process, findings, and their profound ramifications.

2. Theoretical Background

Effective flood risk management and assessment are underpinned by two fundamental elements: risk communication and risk perception (Birkholz et al., 2014). These components play a pivotal role in guiding strategies to mitigate the devastating consequences of flooding.

2.1. Risk Communication

Risk communication takes center stage in flood risk management as a crucial link between technical expertise and vulnerable communities (Kellens et al., 2013). It transcends the mere conveyance of data; instead, it encompasses the art of fostering deep comprehension of flood risks and empowering informed decision-making. By effectively communicating flood risk, individuals, communities, and policymakers can take proactive measures to reduce the potential impacts of flooding (Filatova et al., 2011; Shao et al., 2017; Sermet and Demir, 2022).

The objectives of risk communication in flood management are multifaceted. They include enhancing preparedness by educating communities about flood risks and preparedness measures, building resilience through advocacy for flood-resilient infrastructure and land-use planning, elevating awareness about the potential consequences of flooding, and facilitating decision-making by providing decision-makers with clear and accurate information (O'Sullivan et al., 2012).

However, the path to effective flood risk communication is fraught with challenges. The complexity of flood risk information, which includes intricate hydrological data, topographical maps, and probabilistic forecasts, poses a significant hurdle (Grimaldi et al., 2019; Rumson & Hallett, 2019). Moreover, risk perception is influenced by cognitive biases, past experiences, and social dynamics (Tanir et al., 2024), which can lead to varying interpretations of risk (Voinson et al., 2015). Additionally, the inherent uncertainty in flood forecasts necessitates a delicate balance in communicating risk without causing undue panic or complacency (Thompson et al., 2020).

2.2. Risk Perception

Understanding how individuals perceive flood risks is critical to flood risk management. Risk perception is influenced by numerous factors, including personal experiences with past floods, information from the media and authoritative sources, social networks (Li et al., 2020), and psychological biases (Walkling & Haworth, 2020). These factors can collectively shape individuals' perceptions of risk and their willingness to take action in response to flood warnings.

To address these challenges and align risk perception with actual flood risks, communicators can employ various strategies. These strategies include tailored messaging that caters to the specific needs and concerns of different community groups, engagement and participation of communities in the risk assessment process, transparency and honesty about uncertainties in flood risk assessments, and continuous education and awareness campaigns to reinforce risk understanding and preparedness (Figueiredo et al., 2009; Henriksen et al., 2018).

The interplay between risk communication and risk perception is dynamic, where effective communication can positively influence risk perception, ultimately leading to better-informed decisions and improved flood risk management strategies (Tanner & Árvai, 2018; Wood et al., 2012; Demiray et al., 2023). This paper will explore the intricate relationship between these two elements and their impact on flood vulnerability assessment, laying the groundwork for integrating physical and socioeconomic indicators into the Nines of Safety framework in subsequent chapters.

3. Risk Communication Methods

In the United States, flood risk communication is a critical component of flood risk management, aimed at raising awareness, enhancing preparedness, and fostering community resilience to prepare cities for the future environmental challenges (Beck et al., 2010). Several key strategies and challenges characterize the country's current landscape of flood risk communication.

3.1. Federal Agencies and Standards

The United States, like Europe, has established common standards for flood risk communication. The Federal Emergency Management Agency (FEMA) is a central authority responsible for flood hazard mapping and risk communication. FEMA's Flood Insurance Rate Maps (FIRMs) are a cornerstone, delineating flood zones and risk areas (Li et al., 2023). These flood maps serve as a fundamental resource for floodplain management and insurance (Li and Demir, 2022). Additionally, the National Oceanic and Atmospheric Administration (NOAA) operates the National Weather Service (NWS), providing timely flood forecasts, watches, and warnings (Beattie et al., 2002).

3.2. Community-Based Initiatives

At the local level, government agencies, emergency management organizations, and non-profit groups play vital roles in flood risk communication (Mitchell et al., 2008). These entities employ community-based initiatives, such as public outreach campaigns, town hall meetings, and educational programs (Mulyasari & Shaw, 2014). The objective is to engage communities in understanding their flood risks, evacuation routes, and emergency response protocols. These efforts are particularly crucial in flood-prone areas along rivers, coasts, and vulnerable low-lying regions (Adikari et al., 2010; De Sherbinin et al., 2012).

3.3. Technological Advancements

In the United States, technological advancements have significantly transformed flood risk communication. The widespread use of smartphones and the internet has led to the development of mobile apps and websites dedicated to delivering real-time flood information. Recent developments in web technologies, virtual and augmented reality systems, and artificial intelligence provide significant opportunities in flood risk communication. FEMA's Flood Map Service Center (FEMA, 2003) and NOAA's Flood Information Portal offer online access to flood maps, data, and hazard information. The Wireless Emergency Alerts (WEA) system enables government agencies to send geographically targeted emergency messages to mobile devices during flood events.

3.4. Flood Risk Communications Approaches

Flood risk communication requires various strategies, which can be classified into two main categories: quantitative and qualitative methods (Table 1). To evaluate comprehension and efficacy, quantitative methodologies encompass risk perception surveys and agent-based modeling. Flood risk mapping, providing real-time water level data, and disseminating flood warnings collectively provide up-to-date and timely information. The Protection Motivation Theory (PMT) offers a theoretical framework for understanding and analyzing behavioral responses.

Qualitative methodologies encompass the utilization of narrative communication, which emphasizes the use of tales to convey causal links. Community-based approaches encompass community members' active engagement in risk management planning, hence fostering a deeper comprehension of the subject matter. These tactics jointly improve the effectiveness of flood risk communication by addressing a broad audience's various preferences and demands.

Table 1. Flood risk communication approaches

Type of Approach	**Communication Approach**	**Description of the Approach**
Quantitative Approaches	Risk Perception Surveys	Surveys can assess how well individuals understand and perceive flooding dangers, are prepared, and respond to risk communication techniques. These studies typically use the Likert scale, which asks participants to score their agreement or disagreement with a sequence of topics as seen in Bubeck et al. (2012).
	Agent-Based Modeling	NetLogo V 5.2.0 is the modeling application used by Tisue & Wilensky (2004) for the modeling. The program replicates the timing and frequency of household preventive measures and assesses the efficiency of various flood risk communication tactics. Even when personalized information reaches fewer people, it can still be far more effective than the top-down government communication approach regarding flood risk.
	Flood Risk Mapping	Online maps show probable flood hazard locations and distinguish between high-, medium-, and low-risk levels. intended to increase people's awareness of the danger of floods to people who live in high-risk locations prevailing throughout most of the USA and EU.
	Real-time Water Level information	Online hydrographs are available for real-time river levels tracked at river gauging stations. These records are updated every 15 minutes when there is flooding. These hydrographs also show the maximum recorded level and the level above which flooding is likely to occur. It intended to make it possible for locals to monitor river levels and choose whether to act in the event of potential flooding.
	Flood Warnings	Flood warning systems (Fielding et al., 2007) are intended that persons at risk start monitoring local river levels at the flood alarm stage and start putting flood-resilient measures into place at the Flood Warning Stage. There are three alarm levels issued. It is intended to guide those vulnerable on when to act in the event of a probable flood.
	Protection Motivation Theory (PMT)	The interaction between the various factors that may help to cause behavioral reactions to risk information is explained and given a broad framework by PMT (Rogers, 1975)
Qualitative Approaches	Narrative Communication	According to Hilton et al. (2008), narratives or stories influence risk communication. Descriptions that explains the effects of earlier "100-year" or "500-year" floods can help people visualize these occurrences and comprehend their potential severity (Wing et al., 2022).
	Community-Based Approaches	Participating in flood risk management planning, where concepts like "100-year flood" are defined and debated, can help people better comprehend the risks involved. This technique is discussed in a study by Kellens et al. (2013).

4. Methods

4.1. Nines of Safety Approach

Integrating the Nines of Safety concept into flood risk communication holds promise in enhancing our ability to convey the complexities of flood vulnerability. This tool simplifies assessing and quantifying risk, making it accessible to a broader audience, from community members to policymakers. By mapping flood vulnerability levels onto the Nines of Safety scale, stakeholders gain a visual and intuitive representation of the associated risks. Moreover, the Nines of Safety concept allows for standardized risk assessment, which is particularly valuable when comparing flood vulnerability across diverse geographic regions or assessing the effectiveness of mitigation strategies. This standardized approach minimizes ambiguity and ensures consistent risk communication.

The NoS concept, initially introduced by the esteemed mathematician Terence Tao (2021) in his insightful blog post entitled "Nines of Safety: A Proposed Unit of Measurement of Risk", tackled a fundamental issue that arises in ordinary conversations - the comprehension of percentages when quantifying probabilities and proportions. Percentage rates are frequently used in talks related to risk, but they can be challenging to understand, especially for people who do not have a strong background in mathematics. The central point is the contextual intricacies that significantly shape the evaluation of whether a particular percentage represents a favorable or unfavorable result. For example, let us examine the case of a two-party electoral contest: a narrow difference of 51% to 49% may be seen as an intensely competitive race. In comparison, a margin of 55% to 45% might be seen as a clear expression of popular support, and a result of 60% to 40% could be regarded as a resounding triumph.

On the other hand, within the healthcare domain, medical intervention with a success rate of 51%, 55%, or 60% would be considered unduly hazardous, particularly given the severe consequences associated with an unsuccessful outcome. However, it is intriguing that even a procedure with a likelihood of non-fatality as high as 90% or 95%, corresponding to a 10% or 5% danger of death, respectively, is not regarded casually. Inequalities in risk perception highlight the contextual sensitivity of percentages in communicating threats.

Tao (2021) proposed the notion of NoS as a viable metric for evaluating the likelihood of evading undesired events, such as accidents, diseases, or fatalities, in reaction to this particular difficulty. The NoS system employs a quantitative approach to assess safety standards by measuring the frequency of the digit 9 in the chance of effectively preventing adverse events. As an illustration, a success rate of 90% can be represented as one "Nine of Safety," while a success rate of 99% can be expressed as two nines. Similarly, a success rate of 99.9% can be denoted as three nines, and so on. By implementing this system, we aim to establish a more user-friendly and universally accepted methodology for evaluating and conveying risk, specifically within flood susceptibility.

In harmony with the NoS concept, Tao (2021) offers a precise framework for quantifying safety levels concerning various activities affecting one or more individuals over a specified time frame. It establishes that a workout with a probability "p" of yielding a 'safe' outcome and a complementary probability (1-p) of resulting in an 'unsafe' effect can be characterized by a specific number of Nines of Safety, denoted as "k." The formula rigorously determines this quantification:

$$k = -\log_{10}(1-p) \qquad \text{Eq. 1}$$

where log_{10} the logarithm to base ten plays a pivotal role in the computation. This formula is equivalent to

$$p = 1 - 10^{-k} \qquad \text{Eq. 2}$$

which defines the relationship between probability and Nines of Safety, offering a mathematical foundation for our approach. Another notable aspect of this notion is its recognition of the existence of uncertainties inherent in the measurement of probabilities and the inherent faults in the assumptions and approximations used in subsequent analyses. As a result, the measurement of NoS is limited to the first decimal place, and all evaluations are approximated to the nearest tenth of a “Nine of Safety”.

A conversion table is provided to enhance comprehension and practical implementation (Table 2), which establishes a correlation between percentage rates of success (referred to as 'safe outcome') and failure (referred to as 'unsafe outcome') and the appropriate quantity of Nines of Safety. As an illustration, a success rate of 90% can be represented as a single “Nine of Safety”, but a success rate of 99% corresponds to two nines, and a success rate of 99.9% suggests three nines, and so on. This mathematical framework enables the accurate conversion of probabilities into Nines of Safety, augmenting our capacity to communicate intricate risk information properly.

Presented below is a tabular representation illustrating the correlation between percentage rates denoting successful outcomes (referred to as the safe result), unsuccessful outcomes (referred to as the unsafe outcome), and the quantification of safety in terms of the number of nines.

Table 2. Probability of success and failure with NoS rating

Success Rate, p	**Failure Rate, $1-p$**	**Number of Nines, k**
0%	100%	0.0
50%	50%	0.3
75%	25%	0.6
90%	10%	1
95%	5%	1.3
99%	1%	2
99.9%	0.1%	3
99.98%	0.02%	3.7
99.99%	0.01%	4
100%	0%	Infinite

Therefore, in the absence of any safety measures, failure is inevitable. However, each additional safety measure decreases the failure rate by a factor of ten. In an optimal scenario, individuals would possess an inexhaustible level of safety measures to mitigate all potential risks. However, providing absolute assurances of success is impossible, limiting the attainable level of safety to a finite number of nines in every specific circumstance. In a pragmatic sense, striving for a substantial level of safety, preferably with a high number of nines, that is, within reasonable expectations, is advisable. However, it is not feasible nor rational to insist on an infinite degree of safety.

4.2. Nines of Safety in Flood Risk Communication

Based on this theoretical framework, the level of safety against a particular danger, measured in terms of the number of nines, is not fixed. It is contingent upon two factors: (a) the quantity of indicators linked to the risk and (b) the duration of exposure to the risk. Reducing the number of nines can be achieved by exposing harmful elements or prolonging exposure time. Conversely, the number of nines can be increased by exposing positive indications or reducing the duration of exposure.

Flood risk assessment encompasses many indicators, encompassing physical parameters and socioeconomic factors. Practical analysis demands a comprehensive understanding of these indicators and proficiency in relevant technologies, such as Geographic Information Systems (GIS) and database management. Decision-makers entrusted with this task must possess a wealth of data and the knowledge and expertise to model and interpret it accurately.

While data driven approaches provides opportunities for rapid flood map generation with limited data or computational needs, the accessibility of comprehensive flood risk maps, which demand substantial computational and data resources, remains challenging for many communities. Disparities exist among geographic areas; some are endowed with abundant data resources, including statewide and community-level flood map repositories, demographic data encompassing population, income, and age, and geophysical information, such as soil composition, Digital Elevation Models (DEM), drainage networks, and land use patterns. When strategically integrated, these extensive datasets hold immense potential for conducting a comprehensive flood risk assessment.

By amalgamating these datasets and employing advanced methodologies, it becomes feasible to gauge flood risk with precision and present it within the context of the NoS scale. This approach enhances the accuracy of risk assessments and enables more effective communication of flood vulnerabilities, fostering informed decision-making within communities and among stakeholders.

4.2.1. Nines of Safety at Different Flood Return Period Zones

The element of time duration in the NoS framework is essential for a comprehensive flood risk assessment (Table 3). The chance of avoiding undesired events is a valuable metric subject to change and evolution over time. For example, a geographic area assigned a particular NoS rating may have a heightened probability of flooding if people dwell in that vicinity for an extended duration. The temporal component in flood risk assessment includes a dynamic element, as the likelihood of encountering a flood event may increase with extended periods of habitation. Acknowledging the relationship between the concept of NoS and the period allows for enhanced accuracy in risk communication and the development of long-term strategies for flood preparedness. This statement emphasizes the significance of considering both spatial and temporal aspects when assessing the susceptibility of populations to floods. Doing so eventually improves the efficacy of flood risk management endeavors. The following equation expresses the likelihood of flooding:

$$likelihood\ of\ flooding = \left\{1 - (1 - probability)^{duration}\right\} \qquad \text{Eq. 3}$$

Table 3. NoS rating with flood return period (years)

Flood Return period in years	**% Chance to occur in a year**	**Safety (%)**	**Safety rating in the NoS scale**
2	50	50.0	0.3
5	20	80.0	0.7
10	10	90.0	1.0
20	5	95.0	1.3
50	2	98.0	1.7
75	1.3	98.7	1.9
100	1	99.0	2.0
200	0.5	99.5	2.3
500	0.2	99.8	2.7
1000	0.1	99.9	3.0

4.2.2. Physical Parameters of Flood Risk Assessment

Similar to the time duration, adding one indicator will affect the overall safety rating based on the relationship between the indicator and the risk according to the NoS concept. Even if a precaution is less than one hundred percent effective, it will add additional Nines of Safety against the risk. Suppose an activity carries "k" NoS against a particular risk, and a distinct precaution can independently protect against that risk with "l" Nines of Safety (that is to say, the probability that the protection is adequate is $1 - 10^{-l}$. Consequently, the number of nines in the activity increases from "k" to "$k+l$" when this precaution is taken (Tao, 2021).

Flood risk evaluation requires a thorough approach considering physical elements to assess a region's susceptibility. Flood risk is assessed using Digital Elevation Models (DEM), soil type, land use, drainage density, etc. (Littidej & Buasri, 2019; Saleem et al., 2019; Vignesh et al., 2021). For this study, we are only considering these four parameters, i.e., elevation, soil type, land use, and drainage density. Other parameters can be integrated within this scale in the same manner according to their importance in the flood risk assessment.

Digital Elevation Models (DEMs) provide accurate elevation data and reveal a region's topography (Rabus et al., 2003). This trait helps identify flood-prone lowlands. Flood modelers may define floodplains, identify flood-prone areas, and estimate floodwater levels using Digital Elevation Models (Manfreda et al., 2011). The low elevation is prone to be affected by flood with greater risk and vice versa (Tonn & Guikema, 2018). Soil composition significantly affects flood risk assessment (Wang et al., 2015). Various soil types have different permeabilities, which affect water infiltration (Huat et al., 2006). Impermeable soils like clay can increase surface runoff and floods (Kelly, 2018; Sjöman & Gill, 2014). Sandy or loamy soils absorb water better, reducing floods (Palmer & Smith, 2013; White, 2008).

The distribution and management of land in an area, known as land use, affects flooding susceptibility. Urbanization may increase runoff and flooding by expanding impervious surfaces like roads and buildings (McGrane, 2016). However, locations with plenty of open land or green spaces can absorb more water and reduce floods (Farrugia et al., 2013; Givoni, 1991). The size and effectiveness of natural and manufactured drainage networks, including rivers, canals, and stormwater infrastructure, are measured by drainage density (Peacock et al., 2021). Increased drainage density may help convey surplus water more efficiently, reducing flooding risk (Pallard et al., 2009). Inundation may be more likely in areas with poor drainage (Johnson et al., 2019).

4.2.3. Socioeconomic Parameters

Socioeconomic factors are equally significant in predicting vulnerability and driving mitigation options for flood risk (Djordjević et al., 2011). Income, age, and population are essential socioeconomic factors in flood risk assessment (Cançado et al., 2008; Chakraborty et al., 2020; Carson et al., 2018). Community resilience to floods depends on income. Due to budgetary constraints, lower socioeconomic households often struggle with pre- and post-flood preparedness and recovery (Lamond et al., 2015). Vulnerable people may struggle to afford flood insurance, emergency supplies, or home repairs after a flood (Rhodes & Besbris, 2022). However, households with greater incomes may be better able to dedicate resources to preventative measures and a faster recovery. Economic inequalities are essential when assessing flood hazards.

Flood risk dynamics are affected by population demographics, particularly age groups (Faber, 2015). In flood circumstances, seniors and small children often need special care, evacuation, and refuge. Age group distribution evaluation in flood-prone locations helps customize evacuation strategies, allocate resources efficiently, and meet the needs of vulnerable age cohorts (Isia et al., 2023). Flood risk is estimated using the socioeconomic status of the population. High-population areas may have more trouble evacuating and organizing storm response. High population densities can further worsen the socioeconomic effects of floods, such as forced relocation, financial losses, and strain on public infrastructure and resources (Chan, 2014).

Understanding population distribution and density is essential to estimating flood damage and identifying vulnerable places. Including socioeconomic considerations with physical factors in flood risk assessment models improves susceptibility assessments. By considering income disparities, age group distributions, and population densities, stakeholders can tailor flood mitigation, preparedness, and response methods to meet the needs and challenges of different socioeconomic groups in flood-prone communities (Teo et al., 2018). A comprehensive strategy improves comprehensive flood resilience and equity. According to Tao (2021), if a group of *n* people are independently exposed to a given risk. If there are at most *m* nines of individual safety (Eq. 4) against that risk, there is at least a 50% chance that one group member is affected by the threat.

$$m = log_{10}\frac{1}{1-2^{\frac{-1}{n}}} \qquad \text{Eq. 4}$$

If individually there are *k* Nines of Safety, then the probability that all the members of the group avoid the risk is given by Eq. 5,

$$(1-10^{-k})^{m} \leq \frac{1}{2} \qquad \text{Eq. 5}$$

which is equivalent to *k* as given below in Eq. 6.

$$k \leq log_{10}\frac{1}{1-2^{-\frac{1}{n}}} \qquad \text{Eq. 6}$$

The safety rating for an individual remains constant at "0". When evaluating a partnership involving two individuals, there is a marginal decrease of -0.3 in safety. When considering including parents in the three-person family unit, the safety rating undergoes an additional reduction of -0.5. Within a larger family unit of ten individuals, the decline's magnitude intensifies to a negative one-point zero value. When expanding the scope to encompass a more significant cohort, such as a workplace including 100 individuals, a noticeable decline of 2.0 units in safety becomes apparent. The observed pattern persists as the number of individuals in the group increases. Specifically, when added with 1,000 individuals, an area demonstrates a decrease of -3.0. In places characterized by high population density, the degree of decline in safety is further accentuated (Table 4), as exemplified by a city with a population of one million experiencing a safety reduction of -6.0.

Table 4. NoS rating with added population.

Group	**Reduction in Safety**
You (1 person)	0.3
You and your partner (2 people)	0.5
You, your partner, and three children (5 people)	0.9
A workplace of 100 people	2.2
A city of 1 million people	6.2
A state of 10 million people	7.2

This idea becomes particularly relevant when evaluating hazards within group settings, demonstrating that as the size of the group expands, the probability of at least one person encountering the risk significantly escalates (Table 4). Although it should be noted that these reductions in safety may be somewhat idealized and may not comprehensively consider correlations and dependencies within groups, they provide a significant foundation for comprehending the changing dynamics of risk in different spatial situations.

4.2.4. Adding Multiple Indicators into Safety Scale

In practical contexts, it is common for multiple physical factors to exhibit interdependencies rather than existing in isolation. Conversely, these traits occur in conjunction, contributing to the overall formation of the flood risk landscape. Therefore, it is advisable to include many factors in the evaluation procedure to comprehend the intrinsic safety level within a particular area comprehensively. This requires a comprehensive understanding of the interaction between these variables and their combined impact on the vulnerability to flooding. Cikmaz et al. (2023) have comprehensively analyzed the complex interconnections using the Analytic Hierarchy Process (AHP) to develop a systematic framework. The research delineates the subsequent interconnections between the factors (Table 5):

Table 5. Relationship of multiple physical parameters.

Geophysical Parameters	Land Use	Elevation	Soil Type	Slope	River Density
Land Use	1	0.67	0.67	1	0.67
Elevation	0.5	1	0.5	1	1
Soil type	0.5	0.67	1	0.5	1
Slope	1	0.5	0.67	1	0.5
River Drainage Density	0.5	1	1	1	1

This information will help us understand the safety scale when we consider a new parameter in our safety scale and combine multiple parameters into the scale. If we classify the elevation into ten distinct classes using the natural breaks classification method, each type will pose a different set of safety (Table 6).

Table 6. Possibility (%) of flooding and NoS rating.

	Highest Level	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Lowest Level
Possibility of flooding (%)	50	20	10	5	2	1.33	1	0.5	0.2	0.1
In Nines of Safety scale	0.301	0.096	0.04	0.02	0.008	0.005	0.004	0.002	0.0008	0.0004

5. Results and Discussion

5.1. NoS and Time Duration

As discussed in the methodology section, the NoS largely depends on the time scale. When a person is exposed to a specific risk for a long time, the overall NoS affected by the risk increases over time. People staying in precarious places become more vulnerable day by day. So, the broad NoS scale would be like Table 7 over a certain period. Here, we have considered a 30-yr period as the mortgage is typically considered for 30 years. We can see from the table that NoS drops 3 to 1.5 in a 1000-yr flood zone area in this 30-yr mortgage time. On the other hand, it becomes zero (0) in 4 years for the 2-yr return period flood zone, indicating that it becomes entirely unsafe to stay in that particular zone for more than three years.

Table 7. NoS rating with time scale.

Nines of Safety Rating Scale										
Duration (year) / Return Period	**1000**	**500**	**200**	**100**	**75**	**50**	**20**	**10**	**5**	**2**
1	3.0	2.7	2.3	2.0	1.9	1.7	1.3	1.0	0.7	0.3
2	2.7	2.4	2.0	1.7	1.6	1.4	1.0	0.7	0.4	0.1
3	2.5	2.2	1.8	1.5	1.4	1.2	0.8	0.6	0.3	0.1
4	2.4	2.1	1.7	1.4	1.3	1.1	0.7	0.5	0.2	0.0
5	2.3	2.0	1.6	1.3	1.2	1.0	0.6	0.4	0.2	0.0
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26	1.6	1.3	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
27	1.6	1.3	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
28	1.6	1.3	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
29	1.5	1.2	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
30	1.5	1.2	0.9	0.6	0.5	0.3	0.1	0.0	0.0	0.0

5.2. Physical Parameters and NoS Rating

5.2.1. Land Use (Water Bodies)

Geophysical parameters have a strong correlation with flood risk and have a substantial impact on the overall safety assessment of a particular location. Our investigation focused on the influence of land use where water bodies pose the highest flood risk level (Cikmaz et al., 2023). The presence of bodies of water plays a crucial role, with areas near bodies of water generally associated with increased safety concerns. The NoS rating, the foundation of our evaluation, depends on classifying a location's water body characteristics. According to Cikmaz et al. (2023), their research demonstrates the direct relationship between water body classification and flood risk. For instance, locations near bodies of water with the lowest category pose the most significant inundation risk (~ 90%). In contrast, those near bodies of water with higher classification correspond to progressively improved safety levels on the NoS scale. By classifying water body characteristics into distinct categories, our study provides a nuanced understanding of flood vulnerability, making it a valuable resource for precise risk assessment and strategic flood risk management planning.

According to our previous discussion, adding the time duration dramatically influences the overall safety rating. Table 8 shows the NoS Rating Scale for land usage, emphasizing waterbodies. This scale quantifies flood safety depending on event duration in years or return period. NoS values range from 0.0 (lowest safety level) to 3.0 (highest safety level). In the first row (Duration = 1 year), NoS values for return periods 1000, 500, 200, etc., are analyzed to determine safety. NoS 3.0 indicates strong safety, whereas NoS of 0.0 indicates flooding vulnerability. Table 8 shows how safety values decline with duration or return period, stressing the reducing protection against flooding.

Table 8. NoS rating for waterbody land use type at different flood zones.

Land Use (Water Bodies)										
Duration (year) / Return Period	**1000**	**500**	**200**	**100**	**75**	**50**	**20**	**10**	**5**	**2**
1	3.0	2.7	2.3	2.0	1.9	1.7	1.3	1.0	0.7	0.3
2	2.7	2.4	2.0	1.7	1.6	1.4	1.1	0.8	0.5	0.2
3	2.6	2.3	1.9	1.6	1.4	1.3	0.9	0.6	0.4	0.1
4	2.4	2.1	1.7	1.5	1.3	1.2	0.8	0.5	0.3	0.1
5	2.3	2.0	1.7	1.4	1.2	1.1	0.7	0.4	0.2	0.1
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26	1.6	1.3	1.0	0.7	0.6	0.4	0.2	0.1	0.0	0.0
27	1.6	1.3	0.9	0.7	0.6	0.4	0.2	0.1	0.0	0.0
28	1.6	1.3	0.9	0.7	0.5	0.4	0.2	0.1	0.0	0.0
29	1.6	1.3	0.9	0.6	0.5	0.4	0.2	0.1	0.0	0.0
30	1.6	1.3	0.9	0.6	0.5	0.4	0.2	0.1	0.0	0.0

5.2.2. Land Use (Urban Land Complex)

For urban land complexes, the overall risk of water bodies is around 80% (Cikmaz et al., 2023). The flood risk is significantly influenced by agricultural cropland and vegetation (Yildirim and Demir, 2022), accounting for nearly 75% of the overall contribution. This highlights the tremendous impact these factors have on susceptibility. In contrast, our assessment reveals that open spaces, forests, and wetlands demonstrate the slightest vulnerability to flooding. When the integration of these diverse land cover categories occurs, the resulting safety rating within the NoS scale indicates the matching level of safety. This comprehensive approach thoroughly depicts flood risk and emphasizes the crucial significance of land cover types in accurate risk assessment and management measures. So, considering urban land complex, the overall NoS would be the following (Table 9).

Table 9. NoS rating for urban land complex type land use type at different flood zones.

Land Use (Urban Land Complex)										
Duration (year) / Return Period	**1000**	**500**	**200**	**100**	**75**	**50**	**20**	**10**	**5**	**2**
1	3.1	2.8	2.4	2.1	2.0	1.8	1.4	1.1	0.8	0.4
2	2.8	2.5	2.1	1.8	1.7	1.5	1.1	0.8	0.5	0.2
3	2.6	2.3	1.9	1.6	1.5	1.3	0.9	0.7	0.4	0.2
4	2.5	2.2	1.8	1.5	1.4	1.2	0.8	0.6	0.3	0.1
5	2.4	2.1	1.7	1.4	1.3	1.1	0.7	0.5	0.3	0.1
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26	1.7	1.4	1.0	0.7	0.6	0.5	0.2	0.1	0.1	0.1
27	1.7	1.4	1.0	0.7	0.6	0.5	0.2	0.1	0.1	0.1
28	1.7	1.4	1.0	0.7	0.6	0.5	0.2	0.1	0.1	0.1
29	1.6	1.3	1.0	0.7	0.6	0.5	0.2	0.1	0.1	0.1
30	1.6	1.3	1.0	0.7	0.6	0.4	0.2	0.1	0.1	0.1

5.2.3. NoS Rating for Varying Elevations

If we add the elevation value to Nines of Safety method and time duration to stay at that place, the overall NoS rating would be the following (Table 10):

Table 10. NoS rating at different elevation levels.

Elevation										
Duration (year) / Safety Level	**Highest Level**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**	**Class 7**	**Class 8**	**Class 9**	**Lowest Level**
1	3.3	2.8	2.3	2.0	1.9	1.7	1.3	1.0	0.7	0.3
2	3.0	2.5	2.0	1.7	1.6	1.4	1.0	0.7	0.4	0.1
3	2.8	2.3	1.9	1.5	1.4	1.2	0.9	0.6	0.3	0.1
4	2.7	2.2	1.7	1.4	1.3	1.1	0.7	0.5	0.2	0.0
5	2.6	2.1	1.7	1.3	1.2	1.0	0.6	0.4	0.2	0.0
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26	1.9	1.4	1.0	0.7	0.5	0.4	0.1	0.0	0.0	0.0
27	1.9	1.4	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
28	1.9	1.4	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
29	1.8	1.3	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
30	1.8	1.3	0.9	0.6	0.5	0.3	0.1	0.0	0.0	0.0

5.2.4. NoS Rating for Varying River Drainage Density

We have considered the Euclidean distance in kilometers for river drainage density. The classification is based on the natural break classification method. There is a linear relationship between flood risk and river drainage density. The higher the distance, there is more safety, or the NoS rating is higher for that. River drainage density and slope pose a similar flood risk, like elevation. So, the overall safety in the nines of the safety scale will be the following (Table 11):

Table 11. NoS rating at different drainage density values.

River Drainage Density										
Duration (year) / Safety Level	**>15 km**	**12-15 km**	**10-12 km**	**7.5-10 km**	**5-7.5 km**	**3.5-5 km**	**2-3.5 km**	**1-2 km**	**0.5-1 km**	**<0.5 km**
1	3.3	2.8	2.3	2.0	1.9	1.7	1.3	1.0	0.7	0.3
2	3.0	2.5	2.0	1.7	1.6	1.4	1.0	0.7	0.4	0.1
3	2.8	2.3	1.9	1.5	1.4	1.2	0.9	0.6	0.3	0.1
4	2.7	2.2	1.7	1.4	1.3	1.1	0.7	0.5	0.2	0.0
5	2.6	2.1	1.7	1.3	1.2	1.0	0.6	0.4	0.2	0.0
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26	1.9	1.4	1.0	0.7	0.5	0.4	0.1	0.0	0.0	0.0
27	1.9	1.4	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
28	1.9	1.4	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
29	1.8	1.3	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
30	1.8	1.3	0.9	0.6	0.5	0.3	0.1	0.0	0.0	0.0

5.2.5. NoS Rating for Varying Slope Values

Steep inclinations are commonly linked to diminished flood vulnerability due to their ability to expedite the downhill movement of water, impeding its accumulation and mitigating the likelihood of flooding. This attribute facilitates adequate drainage and is considered a mitigating element against floods. Like river drainage density, slope (in degree) poses an equivalent possibility to flood risk. The higher the slope value, the NoS rating is lower like drainage density (Table 12).

Table 12. NoS rating for different slope (degree) values.

Duration (year)	**Slope**									
	>15°	**>12-15°**	**>10-12°**	**>8-10°**	**>6-8°**	**>4-6°**	**>3-4°**	**>2-3°**	**>1-2°**	**<1°**
1	3.3	2.8	2.3	2.0	1.9	1.7	1.3	1.0	0.7	0.3
2	3.0	2.5	2.0	1.7	1.6	1.4	1.0	0.7	0.4	0.1
3	2.8	2.3	1.9	1.5	1.4	1.2	0.9	0.6	0.3	0.1
4	2.7	2.2	1.7	1.4	1.3	1.1	0.7	0.5	0.2	0.0
5	2.6	2.1	1.7	1.3	1.2	1.0	0.6	0.4	0.2	0.0
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26	1.9	1.4	1.0	0.7	0.5	0.4	0.1	0.0	0.0	0.0
27	1.9	1.4	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
28	1.9	1.4	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
29	1.8	1.3	0.9	0.6	0.5	0.4	0.1	0.0	0.0	0.0
30	1.8	1.3	0.9	0.6	0.5	0.3	0.1	0.0	0.0	0.0

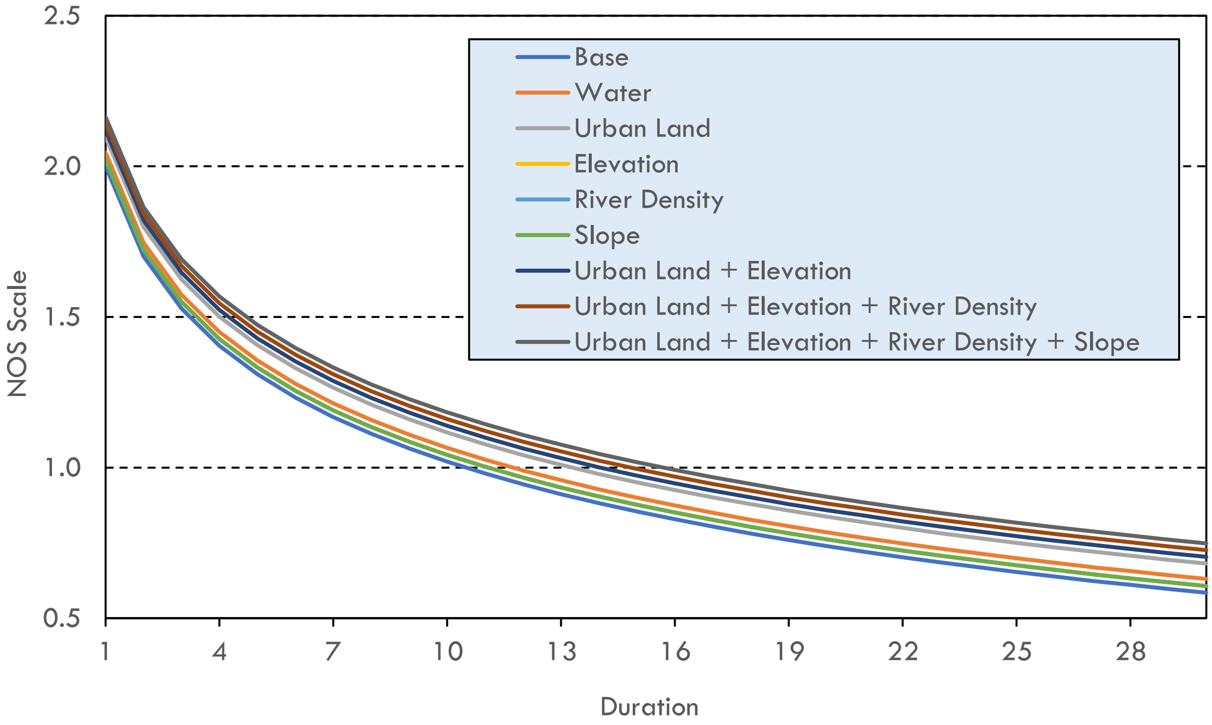

Figure 1. NoS level with different physical parameters.

Combining many individual precautions leads to the accumulation of effects, enabling an elevated safety. This principle remains applicable to the numerous risk variables discussed in this study. For example, implementing precaution A contributes a safety level of 0.7 NoS against a particular risk. Precaution B adds 0.7 NoS, while precaution C provides an extra 1.0 NoS.

Assuming these precautions are independent, the combined implementation of all three measures results in a cumulative safety gain of 2.4 NoS rating against the risk indicated by your indicators (Figure 1).

When assessing the effectiveness of a risk mitigation strategy in a research environment, the crucial inquiry revolves around the extent to which it enhances safety rather than its absolute success or failure. Specifically, the focus is on determining the incremental improvement in safety the method provides, measured in terms of additional nines. Suppose an activity carries k NoS against a particular risk, and an action multiplies the chance of failure by some relative risk R. Then the action removes $log_{10}R$ NoS (if R>1) or odds $-log_{10}R$ NoS (if R<1). The additional action adjusts the probability of failure from 10^{-k} to $R \times 10^{-k} = 10^{-(k-log_{10}R)}$.

5.3. Socioeconomic Parameters in NoS Scale

An area with a 1,000 population should maintain at 3.2 NoS. If 100 people are added in a year to that area, safety will be reduced by 2. So, the overall safety scale (Table 13) would be:

Table 13. NoS rating for adding 100 people.

Duration (year) / Return Period	**1000**	**500**	**200**	**100**	**75**	**50**	**20**	**10**	**5**	**2**
1	1.0	0.7	0.3	0.0	-0.1	-0.3	-0.7	-1.0	-1.3	-1.7
2	0.7	0.4	0.0	-0.3	-0.4	-0.6	-1.0	-1.3	-1.6	-1.9
3	0.5	0.2	-0.2	-0.5	-0.6	-0.8	-1.2	-1.4	-1.7	-1.9
4	0.4	0.1	-0.3	-0.6	-0.7	-0.9	-1.3	-1.5	-1.8	-2.0
5	0.3	0.0	-0.4	-0.7	-0.8	-1.0	-1.4	-1.6	-1.8	-2.0
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26	-0.4	-0.7	-1.1	-1.4	-1.5	-1.6	-1.9	-2.0	-2.0	-2.0
27	-0.4	-0.7	-1.1	-1.4	-1.5	-1.6	-1.9	-2.0	-2.0	-2.0
28	-0.4	-0.7	-1.1	-1.4	-1.5	-1.6	-1.9	-2.0	-2.0	-2.0
29	-0.5	-0.8	-1.1	-1.4	-1.5	-1.6	-1.9	-2.0	-2.0	-2.0
30	-0.5	-0.8	-1.1	-1.4	-1.5	-1.7	-1.9	-2.0	-2.0	-2.0

The negative values represent the opposite of safety. The lower the negative values, the more flood risk is associated. Overall, the areas with the largest population are more susceptible to flood risk than smaller populated areas. Other socioeconomic factors work similarly. If the inclusion of any indicator is associated with 80% effectiveness, there will be an addition of 0.7 of safety in the nines of the safety scale. Including vulnerable populations, including individuals under the age of 5, women, and those over the age of 65, in a certain location greatly increases their vulnerability to flood-related risks compared to other demographic groups. As a result, this leads to an increased likelihood of flood danger overall, resulting in reduced safety assurance. Like the effect of the growing population on the NoS, incorporating this indicator also reduces two decimal places within the scale.

Building upon the preceding discourse, in which the introduction of 100 individuals to a specific region resulted in a proportional decrease in safety by a factor of 2 nines, it is crucial to acknowledge that the demographic makeup of this population plays an essential role in defining the level of safety (NoS) for such location. As an illustration, in the scenario where 25% of the population is classified as belonging to the vulnerable group, it may be inferred that the remaining 75% of the population faces comparatively lower levels of exposure to the hazards associated with such group. As a result, the population segment comprising 25% and identified as vulnerable is responsible for a decrease in safety, quantified as 0.12 nines. This reduction is in addition to the original decrement of 2 nines, resulting in a cumulative Safety of 3.12 for the entire population of 100 individuals. Other socioeconomic factors, like income, race and ethnicity, education, previous experience, government policies, etc., will work similarly and add or reduce NoS based on their association with flood risk.

Table 144. NoS rating for adding 100 people and vulnerable group (25% is women, children under five and aged above 65 years).

Duration (year) / Return Period	**1000**	**500**	**200**	**100**	**75**	**50**	**20**	**10**	**5**	**2**
1	-0.1	-0.4	-0.8	-1.1	-1.2	-1.4	-1.8	-2.1	-2.4	-2.8
2	-0.4	-0.7	-1.1	-1.4	-1.5	-1.7	-2.1	-2.4	-2.7	-3.0
3	-0.6	-0.9	-1.3	-1.6	-1.7	-1.9	-2.3	-2.6	-2.8	-3.1
4	-0.7	-1.0	-1.4	-1.7	-1.8	-2.0	-2.4	-2.7	-2.9	-3.1
5	-0.8	-1.1	-1.5	-1.8	-1.9	-2.1	-2.5	-2.7	-2.9	-3.1
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…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…
26	-1.5	-1.8	-2.2	-2.5	-2.6	-2.7	-3.0	-3.1	-3.1	-3.1
27	-1.5	-1.8	-2.2	-2.5	-2.6	-2.7	-3.0	-3.1	-3.1	-3.1
28	-1.6	-1.9	-2.2	-2.5	-2.6	-2.8	-3.0	-3.1	-3.1	-3.1
29	-1.6	-1.9	-2.3	-2.5	-2.6	-2.8	-3.0	-3.1	-3.1	-3.1
30	-1.6	-1.9	-2.3	-2.5	-2.6	-2.8	-3.0	-3.1	-3.1	-3.1

Table 14 exhibits a continuous trend wherein a rise in duration is accompanied by a steady fall in the number of safety occurrences (NoS), suggesting a decline in safety levels. The extent of this decrease is particularly evident when examining the whole population and the more susceptible group, indicating a heightened vulnerability to flood hazards in the presence of certain demographic factors. The NoS values offer significant insights into the impact of population dynamics, particularly the incorporation of vulnerable populations, on the long-term safety assessment in flood-prone regions (Figure 2). Comprehending these patterns is crucial for policymakers and emergency planners to formulate precise flood risk mitigation and communication plans that consider the evolving population dynamics and their influence on community resilience.

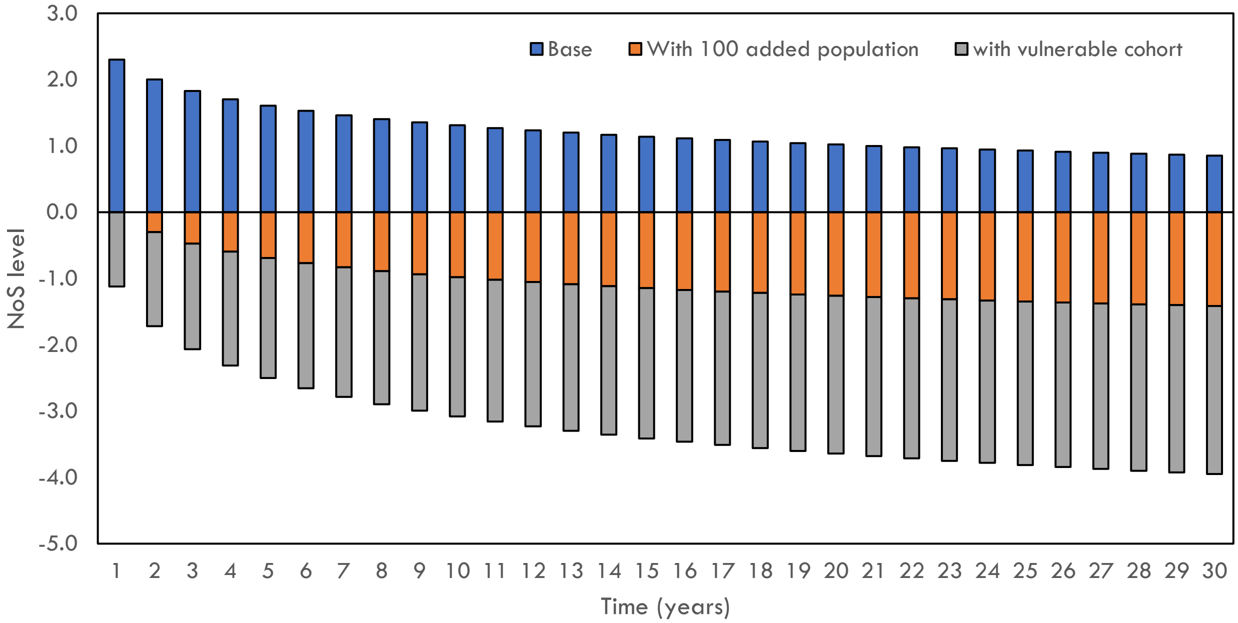

Figure 2. NoS level at 100-year flood zone for two added socioeconomic variables.

6. Conclusion

This study investigates the concept of Nines of Safety (NoS) as a potential metric for evaluating risk, specifically in flood risk assessment. The initial step involved the establishment of a clear definition for the concept of NoS, along with its corresponding mathematical foundation. This elucidation highlighted the importance of NoS in assessing safety levels associated with different activities and locations as they evolve over a given period. The findings of our investigation have revealed a significant correlation between geophysical factors, including Digital Elevation Models (DEMs), soil types, land use, drainage density, and the potential for flood risk. Integrating these parameters yields a thorough comprehension of a geographical area's vulnerability to flooding.

Furthermore, we conducted an in-depth analysis of socioeconomic indicators, such as income levels, age demographics, and population size, acknowledging their significant influence on the configuration of flood vulnerability. The impact of floods on vulnerable populations, including children, women, and older people, was identified as a significant factor contributing to a decrease in the overall number of survivors (NoS) within a given area. Additionally, we investigated the correlation between the period and the number of flooding occurrences, focusing on the impact of residing in a flood-prone location on an individual's level of risk. Furthermore, our discourse encompassed a range of flood risk communication strategies, encompassing both quantitative and qualitative approaches, to augment public consciousness and readiness. Utilizing these methodologies is of utmost importance in transforming NoS rating into practical knowledge that decision-makers and communities can effectively use.

In summary, utilizing the Nines of Safety framework is valuable for assessing and improving risk communication strategies and needs in regions susceptible to flooding. By considering a wide range of geophysical and socioeconomic factors and comprehending their complex interconnections, efforts can be made to enhance the safety and resilience of susceptible communities in response to flood events. The NoS scale offers a concrete metric for evaluating and contrasting the efficacy of risk mitigation strategies, facilitating well-informed decision-making and proactive catastrophe management.

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