Hydrology-Based Coastal Risk Assessment in Charleston, South Carolina: Sea-Level Rise, Land Subsidence, Nuisance Flooding, and the Overlooked Role of Groundwater Attenuation

Author
Trevor Ponto
Independent Researcher
Email: Trevorponto@gmail.com

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Mastodon
@SirLordofDerp@mastodon.social

Abstract

Charleston, South Carolina is among the most flood-exposed cities on the United States Atlantic coast. Tide-gauge records show mean sea level rising at 3.51 mm per year since 1921, while InSAR analyses identify localized subsidence exceeding 4 mm per year, producing effective relative rise of 7 to 8 mm per year. This acceleration explains the increase in nuisance flooding from fewer than 5 days annually in the 1950s to more than 70 days annually today, with NOAA projecting 90 to 120 days by 2030 and over 180 by 2050.

Subsurface dynamics further amplify this trajectory. Rising groundwater reduces soil storage capacity, while saltwater intrusion degrades permeability and vegetation, compounding chronic inundation. FEMA floodplain maps, which designate 35 percent of the peninsula as 100-year floodplain, omit much of the area already subject to routine flooding.

This study integrates oceanic, geodetic, groundwater, and regulatory data into a hydrology-based framework. Results indicate Charleston's flood risk is systematically underestimated. Effective resilience requires accounting for all interacting drivers rather than treating them in isolation.

Keywords: Charleston; coastal flooding; sea-level rise; land subsidence; nuisance flooding; groundwater dynamics; hydrologic attenuation; flood risk assessment

Introduction

Charleston, South Carolina is among the most flood-exposed cities on the United States Atlantic coast. Its vulnerability arises from both natural and human factors. The city is located on a low-lying peninsula bounded by estuarine rivers and tidal marshes, and much of its urban core is less than three meters above mean sea level. Economic and cultural assets, including a major historic district, port facilities, and regional institutions, are concentrated in areas subject to tidal inundation. As a result, relatively modest changes in baseline water levels produce outsized social and economic consequences.

Observational records document the acceleration of these changes. The long-term tide-gauge record at Charleston Harbor (NOAA Station 8665530) shows mean sea level rising at 3.51 mm yr^{-1} (±0.19) since 1921 [3], equivalent to approximately 0.36 m per century. This rate is higher than the twentieth-century global average of 1.7 mm yr^{-1} and continues to increase in the satellite era. Land motion studies further complicate the trajectory. Interferometric synthetic aperture radar (InSAR) analyses identify localized subsidence in parts of the Charleston peninsula exceeding 4 mm yr^{-1} [2]. Where subsidence and eustatic rise combine, effective relative sea-level rise reaches 7–8 mm yr^{-1}, or nearly 8 cm per decade.

The hydrologic implications are apparent in nuisance flooding statistics. The National Weather Service defines the threshold for minor flooding in Charleston at 2.13 m MLLW (7.0 ft) [1]. During the 1950s this threshold was exceeded fewer than five times per year. By 2015 exceedances had increased to 42 days, and in recent years the city has experienced more than 70 nuisance flooding days annually [3]. NOAA's 2022 High Tide Flooding Outlook projects 90–120 flooding days per year by 2030, and more than 180 per year by 2050, under intermediate-to-high scenarios [1,3]. These projections imply that nearly half of all days each year could involve some level of tidal inundation within the next three decades.

Charleston's trajectory is steeper than many other U.S. coastal cities. Norfolk, Virginia, often cited as a flood hotspot, records effective relative sea-level rise of ~5.4 mm yr^{-1} and around a dozen nuisance flooding days per year. Miami, Florida, with ~6.0 mm yr^{-1} relative rise, has recently documented 20–30 such events annually. Annapolis, Maryland recorded 40 events in 2017. Charleston already exceeds 70 flooding days per year, placing it among the most affected cities on the East Coast despite a smaller geographic footprint.

Subsurface processes further amplify this exposure. Shallow groundwater levels are expected to rise in response to sea-level forcing [4]. This reduces unsaturated soil storage, decreases infiltration capacity, and lengthens the duration of surface flooding once water accumulates. Saltwater intrusion can degrade soil structure and vegetation, diminishing natural permeability and reducing the buffering function of marshes and aquifers. Collectively, these changes reduce hydrologic attenuation, the ability of natural and engineered systems to absorb and delay water.

Despite these dynamics, current regulatory frameworks emphasize storm surge rather than chronic flooding. FEMA's National Flood Hazard Layer designates ~35% of the peninsula as 100-year floodplain and ~60% as 500-year floodplain [5]. These categories govern insurance, infrastructure investment, and federal cost-share formulas, but they do not capture the observed 70+ nuisance flooding days per year already occurring outside mapped zones. Local planning documents, including the Stormwater Design Standards Manual [6], the Charleston Water Plan [7], and the U.S. Army Corps of Engineers feasibility study [8], acknowledge sea-level rise and storm drainage but do not treat attenuation as a quantifiable resilience asset.

The objective of this paper is to examine how sea-level rise, subsidence, and groundwater dynamics interact to increase nuisance flooding in Charleston, and to evaluate the under-recognized role of hydrologic attenuation in shaping that risk. The contribution is twofold: (1) integration of observational datasets that are often analyzed separately — tide-gauge records, geodetic land-motion data, hydrogeologic studies, and regulatory flood maps — into a coherent risk framework for Charleston, and (2) framing of attenuation as a measurable component of resilience, which could be incorporated into monitoring networks and planning standards.

Charleston is not unique in facing these dynamics. Subsiding cities worldwide are experiencing the same combined pressure of rising seas and sinking ground. Jakarta and Bangkok represent extreme international cases where land subsidence has already accelerated inundation beyond the capacity of defenses, while New Orleans is the most prominent U.S. example. Charleston is at an earlier stage of this trajectory, but the pattern is clear. The difference is that Charleston still retains a limited window to act before conditions exceed the reach of adaptation strategies.

Study Area and Data

Charleston is located on the Atlantic Coastal Plain of South Carolina at the confluence of the Ashley, Cooper, and Wando Rivers. The city's historic peninsula is bounded by estuarine marshes and tidal creeks that connect directly to Charleston Harbor. Elevations across much of the urbanized core are below three meters above mean sea level, leaving minimal vertical buffer against tidal and storm-driven water levels. The mean tidal range at Charleston is approximately 1.6 meters, meaning relatively small changes in mean sea level can shift the frequency of threshold exceedances.

The city's hydrogeologic setting contributes to its sensitivity. Beneath the surface, Charleston overlies the Coastal Plain aquifer system, which consists of several major units including the Middendorf, Black Creek, and Tertiary sand aquifers [4]. These aquifers are hydraulically connected to the coastal boundary and are responsive to changes in sea level. Rising sea level elevates shallow groundwater tables, reducing the depth to the water table and thereby decreasing the volume of unsaturated soil available for storage. This creates a tighter coupling between surface flooding and subsurface conditions. Saltwater intrusion along aquifer gradients can further reduce soil permeability and harm vegetation, eroding the natural buffering capacity of marshes and wetlands.

The region is also subject to both natural and anthropogenic drivers of land subsidence. Glacial isostatic adjustment contributes a background signal of downward motion along much of the Atlantic seaboard. Superimposed on this, localized subsidence in Charleston is influenced by sediment compaction, infrastructure loading, and possible contributions from historical groundwater extraction. Recent interferometric analyses have identified subsidence hotspots exceeding 4 mm yr^{-1} in parts of the peninsula, which substantially magnifies relative sea-level rise beyond oceanic trends alone [2].

This study draws upon several established datasets and sources:

NOAA tide-gauge records: The Charleston Harbor tide gauge (Station 8665530) provides monthly and annual mean sea-level data beginning in 1921. NOAA also produces annual high tide flooding statistics, which track the number of exceedances of the National Weather Service nuisance flooding threshold [1,3].

Vertical land motion: InSAR-derived vertical land motion estimates are combined with tide-gauge residuals to identify localized subsidence patterns across U.S. coastal cities, including Charleston [2].

Groundwater and hydrostratigraphy: U.S. Geological Survey reports on the Coastal Plain aquifer system provide the framework for understanding groundwater response to sea-level forcing and the potential for saltwater intrusion [4].

Flood hazard mapping: FEMA's National Flood Hazard Layer (NFHL) defines 100-year and 500-year floodplains based on probabilistic storm flooding. In Charleston, approximately 35% of the peninsula falls within the 100-year zone and 60% within the 500-year zone [5].

Local planning references: The City of Charleston Stormwater Design Standards Manual [6], the Charleston Water Plan [7], and the U.S. Army Corps of Engineers Peninsula Flood Risk Management feasibility study [8] provide the design criteria, long-term planning assumptions, and project proposals guiding resilience efforts.

These datasets, while robust individually, are rarely integrated into a single framework. The NOAA tide-gauge record captures oceanic trends but does not reflect subsidence. FEMA flood maps describe storm surge probabilities but not chronic high-tide flooding. Local plans recognize sea-level rise but rarely treat attenuation as a quantifiable parameter. By drawing these elements together, this study provides a hydrology-based assessment of Charleston's evolving risk.

Methods

This assessment applies a structured synthesis rather than the development of a new numerical model. The aim is to integrate multiple observational and regulatory datasets into a single hydrology-based framework for understanding flood risk in Charleston. Five analytical steps were followed:

1. Relative sea-level rise:
Annual and decadal mean sea-level trends were derived from NOAA tide-gauge records at Station 8665530 (Charleston Harbor). These were compared against the National Weather Service nuisance flooding threshold of 2.13 m MLLW (7.0 ft) to evaluate the frequency and trajectory of threshold exceedances [1,3]. Tide levels referenced to MLLW (nuisance threshold) and MHHW (extreme exceedance) are reported in their native datums. Cross-datum comparisons are avoided; all exceedance frequencies are evaluated against thresholds defined within a single datum.

2. Subsidence integration:
Vertical land motion estimates from InSAR analyses were incorporated as modifiers of relative sea-level rise. Locations with greater subsidence were assumed to experience proportionally higher rates of effective rise. This step reflects that relative exposure is driven by both oceanic rise and land motion [2]. Reported subsidence rates reflect neighborhood-scale variation; values exceeding 4 mm per year are local maxima, and uncertainty is carried as qualitative ranges rather than single-point estimates.

3. Groundwater and salinity pathways:
Hydrogeologic information from U.S. Geological Survey reports was used to conceptualize the relationship between sea-level rise, shallow groundwater response, and potential saltwater intrusion. The focus was on how these subsurface dynamics reduce unsaturated soil storage, weaken infiltration, and increase flood persistence [4].

4. Regulatory mapping comparison:
FEMA's National Flood Hazard Layer was used to define the extent of 100-year and 500-year storm flood zones [5]. Observed nuisance flooding frequencies were compared with these mapped categories to identify mismatches between regulatory designations and lived conditions.

5. Attenuation framing:
Local design manuals and planning documents were reviewed to determine how storage, infiltration, and natural buffers are accounted for in resilience planning. The analysis specifically evaluated whether attenuation is treated as a measurable parameter in design or whether it is assumed as background capacity [6–8].

By combining these five elements, the method evaluates Charleston's flood trajectory as the interaction of three processes: (1) steady oceanic boundary shifts, (2) local geologic responses through subsidence, and (3) hydrologic responses in groundwater and soil storage. The framework allows for comparison between observed nuisance flooding, regulatory mapping, and the underlying mechanisms that explain the divergence between the two.

Results

Sea-Level Rise

The tide-gauge record at Charleston Harbor (NOAA Station 8665530) documents a mean sea-level rise of 3.51 mm yr^{-1} (±0.19) over the 1921–2022 period [3]. This equates to 0.36 m per century, substantially above the global twentieth-century average. Rates have increased in the satellite era, consistent with acceleration observed across the U.S. Southeast coast. NOAA's 2022 Sea Level Rise Technical Report projects an additional 0.25–0.30 m of rise by 2050 for the Southeast region under intermediate scenarios, which would elevate baseline water levels beyond current nuisance thresholds on a near-daily basis [1,3].

Source	Rate (mm/yr)	Notes
Tide gauge (NOAA 8665530)	3.51 ± 0.19	Long-term mean since 1921 [3]
Global 20th century average	1.7	Contextual baseline
Subsidence (InSAR)	>4.0	Hotspots across peninsula [2]
Effective relative SLR	7–8	Combined ocean + land motion
Projected by 2050	200–250 mm	Intermediate scenarios [1,3]

Subsidence

InSAR and tide-gauge residual analyses identify subsidence hotspots within Charleston exceeding 4 mm yr^{-1} [2]. When combined with oceanic rise, this results in effective relative sea-level rise of 7–8 mm yr^{-1}, or nearly 8 cm per decade. If sustained, this implies an additional 20–25 cm of relative rise by 2050, compared to ~15 cm if subsidence were ignored. The effect is spatially variable, with certain neighborhoods projected to experience chronic tidal inundation earlier than regional averages suggest.

Nuisance Flooding

Observed nuisance flooding has transitioned from rare to routine. In the 1950s, the National Weather Service nuisance flood threshold (2.13 m MLLW, 7.0 ft) was exceeded fewer than 5 days per year. By 2015, exceedances had increased to 42 days, and in recent years the city has recorded >70 days annually [1,3]. NOAA's 2022 High Tide Flooding Outlook projects 90–120 days per year by 2030 and more than 180 days per year by 2050. These figures indicate that chronic tidal inundation will soon dominate the city's flood exposure, surpassing storm-related flooding in frequency.

Decade	Observed Annual Flood Days	Notes
1950s	<5	Historical baseline
1980s	10–15	Gradual increase
2010s	40–50	Accelerationobserved
2020s	70+	Current condition
2030s	90–120	NOAA projection
2050s	180+	NOAA projection

Groundwater and Salinity

Hydrogeologic studies of the Coastal Plain aquifer system suggest that shallow groundwater levels rise in response to sea-level forcing [4]. A higher groundwater table reduces unsaturated storage in soils, shortens the time to saturation during rainfall, and increases the persistence of ponding once water accumulates. Saltwater intrusion further reduces infiltration capacity by degrading soil structure and vegetation. Laboratory studies indicate 20–40% declines in infiltration rates under salinity stress, which corresponds to measurable losses in attenuation. These dynamics are consistent with reports of reduced drainage performance in Charleston during coincident rainfall and high-tide events.

Regulatory Mapping

FEMA's National Flood Hazard Layer identifies approximately 35% of the Charleston peninsula as 100-year floodplain and 60% as 500-year floodplain [5]. However, chronic nuisance flooding now occurs outside these mapped zones, with more than 70 flood days per year observed across the peninsula. Extreme water level analysis shows that the 1% annual exceedance level in Charleston is only ~1.07 m above mean higher high water (MHHW), underscoring how modest increases in baseline sea level can sharply increase exceedance frequency [3]. The divergence between FEMA storm-based categories and observed tidal inundation highlights a regulatory gap that leaves chronic flooding largely unrecognized in formal planning and funding criteria.

Category FEMA	Map Extent (% peninsula)	Observed Flooding	Notes
100-year floodplain	~35%	Often dry outside storm events	Based on storm surge probabilities [5]
500-year floodplain	~60%	Covers most peninsula	Event-based designation [5]
Chronic nuisance flooding	>70 days/yr, across mapped + unmapped areas	Largely outside FEMA categories	Captured by NOAA stats [1,3]

Discussion

Charleston's results demonstrate how multiple processes interact to accelerate local flood exposure. The city's effective relative sea-level rise of 7 to 8 mm per year, caused by the combination of global ocean rise (~3.5 mm per year) and localized subsidence (>4 mm per year in some areas), is among the highest rates documented along the United States Atlantic coast [2,3]. At this pace, relative sea level will rise 20 to 25 cm by 2050, compared to ~15 cm if subsidence were ignored. This is not a minor adjustment but a 50 to 70 percent increase in effective rise for some neighborhoods. These rates explain the sharp increase in nuisance flooding, from fewer than 5 days annually in the 1950s to more than 70 days annually since 2019, with NOAA projecting 90 to 120 days annually by 2030 and more than 180 days annually by 2050 [1,3].

The role of subsidence and vertical land motion

Risk assessments that rely only on eustatic sea-level projections miss the localized accelerants created by subsidence. In Charleston, InSAR mapping shows neighborhood-scale variation in vertical land motion, with some areas stable and others sinking at more than 4 mm per year [2]. A property in a subsiding area may cross chronic flooding thresholds years earlier than projected by regional sea-level scenarios alone. This spatial variability complicates adaptation planning and underscores the need for high-resolution geodetic monitoring within the city. Ignoring vertical land motion effectively underestimates the rate at which certain neighborhoods are losing functional elevation.

Groundwater, salinity, and attenuation

Surface flooding in Charleston cannot be explained solely by ocean and land levels. Rising shallow groundwater further reduces hydrologic buffering. Studies of the Coastal Plain aquifer system indicate that water tables rise in response to sea-level forcing [4]. As depth to groundwater decreases, the soil's unsaturated zone, which provides storage, shrinks. This shortens the time to surface saturation during coincident rainfall and tidal events.

Salinity intrusion amplifies the effect. Laboratory experiments show 20 to 40 percent declines in infiltration rates under saltwater stress as soil structure collapses and marsh vegetation dies back. In Charleston, this manifests as slower drainage and more persistent ponding in areas where tidal intrusion coincides with rainfall. These processes erode attenuation capacity, meaning the city has less ability to absorb and delay water each year. In practical terms, attenuation that once absorbed a few centimeters of tidal or rainfall input now fails, producing immediate flooding.

Regulatory mismatch and mapping gaps

Despite these realities, current regulatory frameworks remain centered on storm flooding. FEMA's National Flood Hazard Layer maps 35 percent of the peninsula as 100-year floodplain and 60 percent as 500-year floodplain [5]. These designations drive insurance rates, infrastructure planning, and federal funding. Yet chronic nuisance flooding now affects properties outside mapped flood zones, with more than 70 days of tidal flooding annually already observed.

NOAA's extreme water-level analysis indicates that Charleston's 1 percent annual exceedance level is only ~1.07 m above mean higher high water (MHHW) [3]. This means small increments in baseline sea level create disproportionately large increases in exceedance frequency. In other words, the transition from rare flooding to routine flooding is embedded in the city's elevation profile. FEMA maps, designed for probabilistic storm surge, fail to represent this chronic condition. The result is a systematic undercounting of exposure in risk assessments, which affects funding formulas and benefit–cost analyses.

Risk assessment implications

From a risk assessment perspective, Charleston's flood hazard cannot be evaluated in isolation by any single dataset. Sea-level rise alone underestimates effective exposure by 50 percent or more in subsiding neighborhoods. FEMA flood maps understate observed flood frequency by a factor of ten or greater. Groundwater dynamics, which are not included in either framework, further shift the city's flood trajectory by reducing attenuation.

This creates three distinct blind spots:

1.Temporal blind spot: Projections based on ocean rise alone delay expected exposure by years relative to subsiding neighborhoods.

2. Spatial blind spot: FEMA maps identify storm-driven risk areas but omit chronic nuisance flooding, leaving large areas exposed but officially outside mapped risk zones.

3. Process blind spot: Attenuation is unmeasured, despite being central to how surface and subsurface flooding interact.

The combined effect is that Charleston's true flood risk is materially underestimated in official planning frameworks.

Socioeconomic consequences

These underestimations have direct socioeconomic effects. Charleston's downtown historic core, which supports a tourism industry valued at over 8 billion dollars annually, experiences recurring tidal flooding that damages infrastructure and disrupts mobility. Businesses on King Street and Market Street already report lost revenue due to routine inundation. Low-income and historically marginalized neighborhoods such as Rosemont and Gadsden Green face disproportionate exposure, with limited resources to adapt. Public housing units in these areas are especially vulnerable, yet benefit–cost calculations that exclude chronic flooding systematically undervalue protective investment.

Ignoring attenuation compounds inequities. As soils, aquifers, and marshes lose storage capacity, nuisance flooding affects areas that are not flagged in FEMA maps and therefore do not qualify for federal resilience funding. This creates a cycle in which chronic impacts are borne locally, while federal resources flow toward storm-driven hazards.

Lessons from other cities

Other coastal cities provide useful comparisons. Norfolk has begun installing groundwater monitoring wells to integrate subsurface dynamics into flood risk assessments. Miami incorporates aquifer response into its stormwater master planning. Annapolis has tied tidal flooding counts directly to infrastructure planning and zoning. These examples show that it is feasible to operationalize groundwater and attenuation monitoring within resilience frameworks. Charleston has not yet adopted these practices, but the evidence indicates that doing so would substantially improve the credibility of its adaptation strategies.

Synthesis

The data show that Charleston's risk trajectory is accelerating faster than regional averages and that official frameworks do not reflect the true extent of hazard. The effective rate of 7 to 8 mm per year places Charleston in a category with global subsiding megacities, while nuisance flooding already exceeds 70 days annually and is on track to surpass 180 days by mid-century [1–3]. Subsurface dynamics erode attenuation capacity each year, meaning that even if drainage infrastructure remains unchanged, its effective performance is declining.

From a hydrology-based risk assessment perspective, the conclusion is unavoidable: Charleston's flood exposure is being underestimated because assessments are fragmented. Sea-level rise, land subsidence, shallow groundwater, and chronic tidal flooding are treated separately in monitoring and policy, yet they act together to create accelerating risk. The evidence shows that Charleston's true exposure is substantially greater than official designations imply. Unless risk frameworks evolve to account for the combined effect of oceanic rise, vertical land motion, groundwater response, and surface drainage, resilience efforts will continue to trail behind reality.

Conclusion

Charleston’s trajectory demonstrates how interacting processes reshape coastal flood risk when considered together. Tide-gauge records confirm a long-term rise in sea level of 3.51 mm per year, while interferometric studies identify localized subsidence exceeding 4 mm per year. The combined effect is an effective relative rise of 7 to 8 mm per year, among the fastest rates along the United States Atlantic seaboard [2,3]. This trend explains the sharp increase in nuisance flooding, from fewer than 5 days annually in the 1950s to more than 70 days annually in the present decade, with projections exceeding 180 days annually by mid-century [1,3].

These surface observations align with subsurface responses. Rising groundwater reduces the storage capacity of soils, while salinity intrusion alters permeability and damages vegetation [4]. In combination with expanding impervious cover, these processes steadily erode the city’s natural and engineered buffering capacity. Drainage infrastructure designed for stable baselines is losing performance each year as thresholds are surpassed more quickly.

The regulatory frameworks that guide resilience planning do not fully reflect this reality. FEMA floodplain maps remain centered on probabilistic storm surge, designating 35 percent of the peninsula as 100-year floodplain and 60 percent as 500-year floodplain [5]. Yet nuisance flooding now occurs across much wider areas, with frequency already an order of magnitude greater than implied by mapped categories. Federal funding and insurance structures tied to these maps therefore understate present exposure and delay recognition of near-term risk.

The evidence indicates that Charleston’s true hazard profile is not defined by a single driver but by the compounding influence of multiple processes. Sea-level rise, land subsidence, shallow groundwater response, salinity intrusion, and surface drainage constraints converge to accelerate the onset and persistence of flooding. Each process has been documented individually, but integration is essential to capture the scale and urgency of the risk.

From a hydrology-based risk assessment perspective, Charleston represents a clear case where official designations lag behind physical reality. Effective resilience will require frameworks that account for all major pathways of flood hazard rather than emphasizing storm surge alone. Monitoring networks that integrate sea level, land motion, groundwater, and soil storage, combined with policies that recognize chronic tidal inundation, would provide a more credible basis for planning. Charleston retains a narrowing window to act while adaptation remains feasible. The city’s experience also provides a broader lesson for other subsiding coastal communities worldwide, where fragmented assessments continue to underestimate accelerating multi-source flood risk.

Limitations and Data Availability

This study synthesizes publicly available datasets and reports. No new numerical modeling was conducted. Tide-gauge statistics and nuisance flood counts were obtained from NOAA CO-OPS Station 8665530 (Charleston Harbor). Vertical land motion ranges reflect published InSAR analyses for Charleston and nearby coastal cities. FEMA NFHL extents reflect the most recent available map services at the time of drafting. Groundwater and aquifer interpretations are based on USGS Coastal Plain assessments. Each source carries method-specific uncertainty; to avoid over-precision, rates are reported as ranges where appropriate. Source data and references are listed in the manuscript; all are publicly accessible.

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