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Building Climate Resilience in The Bahamas: A Framework for Enhancing Soil and Water Resource Management amidst Saltwater Intrusion

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Abstract

Small Island Developing States (SIDS), like The Bahamas, face growing challenges to fresh water and soil security due to climate change, sea level rise, and unsustainable land use. Saltwater intrusion, intensified by extreme weather events and anthropogenic pressures, threatens the archipelago’s fragile freshwater lenses and limited, sandy soils. A synthesis of available research highlights the unique hydrogeological and pedological characteristics that increase vulnerability to salinization alongside the compounded impacts of groundwater over-extraction, deforestation, urbanization, and pollution. A resilience framework for integrated soil and water management is proposed, incorporating natural and engineered strategies, including halophyte restoration, organic soil amendments, aquifer recharge, and soil flushing techniques. Emphasis is placed on real-time salinity monitoring, adaptive planning, and diversification of drinking water sources. Aligning these strategies with national and sustainable development goals presents an opportunity to safeguard environmental resources and build long-term climate resilience across The Bahamas.

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Introduction

Fresh water is limited in quantity on small islands, creating numerous challenges in providing clean, safe drinking water for island populations. Clean drinking water is essential for human populations as part of Sustainable Development Goal (SDG) 6, Clean Water and Sanitation, within the 2030 Agenda for Sustainable Development, adopted by all United Nations member states. Therefore, safeguarding water sources for human consumption is vital in small island nations.

However, climate change, sea level rise, and over-extraction of fresh water for human use threaten the availability of freshwater on islands (Bedekar et al., 2019; Welsh & Bowleg, 2022; Imig et al., 2025). Physical mixing of the fresh and saline water layers due to storm surges and overwash during intense storms and hurricanes can eradicate freshwater lenses. Flooding of ocean water on land results in increased salinity levels and mobilization of contaminants in groundwater (Mondal et al., 2024). Wave overwash and flooding significantly damage island infrastructure, freshwater lenses' integrity, and small islands' economics (Holding & Allen, 2015). Climate change projections indicate that the effects of wave-driven overwash in low-lying islands will threaten freshwater availability and damage infrastructure to the point that these islands will not be habitable by the mid-21st century, because freshwater aquifers do not have sufficient time to recover between flooding events (Storlazzi et al., 2018). Intense hurricanes are estimated to double in the next 25 years (Bloemendaal et al., 2022), underscoring the urgent need to investigate this issue now. Freshwater lens recovery depends on factors including hydrogeology, amount of recharge, storm characteristics, and length of flooding but generally occurs over months to years (Holding & Allen, 2015; Gingerich et al., 2017; Mondal et al., 2024).

Options for drinking water sources on small islands include surface water, groundwater, ocean water, and rainwater. Yet many Small Island Developing States (SIDS), like The Bahamas, lack fresh surface water sources, such as rivers and lakes. In some instances, islands obtain their public water supply from desalinated ocean water through reverse osmosis. However, desalination's exceptionally high economic and environmental cost makes this option infeasible and undesirable in many locations. Harvested rainwater is weather-dependent and often insufficient to meet the demand. Therefore, groundwater from freshwater lenses typically serves as the most important natural water source for human use on small islands (Bedekar et al., 2019). However, groundwater storage is limited by the amount of rainfall that recharges the groundwater aquifer, extraction from human use, and lateral intrusion from ocean water in the subsurface of the islands.

Soil and groundwater resources are closely interconnected, as soils filter water that infiltrates into the subsurface, while groundwater is stored within soils. Similar to fresh water, soil is a finite resource with serious implications for human health, providing essential ecosystem services such as food production, climate regulation, flood mitigation, and groundwater filtration (Baggaley et al., 2020; Sultan et al., 2023). However, soil ecosystems worldwide face severe threats, with over 34% of agricultural soils already degraded. Current projections suggest that more than 90% of global soils could become degraded by 2050 (Telo da Gama, 2023; Smith et al., 2024). SIDS, including The Bahamas, which already contend with limited soil resources, are particularly vulnerable to accelerated soil loss due to escalating climate change pressures (Klöck & Nunn, 2019). These nations face unprecedented challenges, including sea level rise, saltwater intrusion, and intensifying storm surges, all of which exacerbate stress on fragile soil ecosystems (Food and Agriculture Organizaiton of the United Nations, 2015; Intergovernmental Panel on Climate Change, 2022).

Saltwater intrusion, the encroachment of seawater into freshwater aquifers and soils, has emerged as a dire threat, destabilizing agricultural productivity, contaminating drinking water, and decreasing soil quality (Kirwan & Gedan, 2019; Bayabil et al., 2021). The Bahamas, for instance, is highly susceptible to soil degradation from saltwater intrusion. The islands' close hydrological connection to the ocean, thin topsoil, and increasing frequency of hurricane-induced storm surges magnify this risk (Lam et al., 2014; Deopersad et al., 2020). In 2019, Hurricane Dorian devastated the northern islands, with Grand Bahama experiencing storm surges of up to 7 meters. This event inundated vast areas of the island with saltwater, leaving soils with dangerously high salinity levels (Welsh et al., 2022; Stubbs et al., 2023). Post-disaster studies revealed that these saline soils became unsuitable for plant growth, significantly reducing agricultural yields and threatening ecological balance (Bayabil et al., 2021; Stubbs et al., 2023).

Both natural and anthropogenic factors drive saltwater intrusion in SIDS. Natural mechanisms include sea level rise, storm surges, high tide flooding, and geological vulnerabilities, while human activities, such as excessive groundwater extraction and land development that alters hydrological connectivity, further exacerbate the issue (Parker et al., 2023; Stanic et al., 2024). The geological makeup of The Bahamas has also heightened its soil vulnerability to seawater intrusion. The porous limestone geology allows seawater to infiltrate underground aquifers easily, accumulating salt in soils through capillary action and groundwater intrusion. The islands’ low elevation and proximity to the ocean make them highly susceptible to storm surges, tidal flooding, and seawater overwash, which deposit salt directly into the soil (Yu et al., 2016; Gollo et al., 2024). Additionally, high evaporation rates in the tropical climate concentrate salts in the soil, while limited freshwater resources, as well as human activities like groundwater extraction and deforestation, further exacerbate salinity issues (Lam et al., 2014; Deopersad et al., 2020). Globally, sea level has been rising, and the Intergovernmental Panel on Climate Change (IPCC) projects that sea level will increase by 0.4 meters by 2100 under the best-case scenario, with worst-case projections estimating a 0.8-meter increase. This increase will result in significant land loss and, by extension, the loss of soil resources (Intergovernmental Panel on Climate Change, 2021; Kopp et al., 2014).

Similarly, storm surges commonly associated with hurricanes and intense storm systems reduce available, viable soil and inundate coastal aquifers. In The Bahamas, major storms such as Hurricane Dorian (2019), Hurricane Joaquin (2015), and Hurricane Andrew (1992) resulted in extensive flooding, increasing soil and groundwater salinity levels, which negatively impacted agriculture and left lasting environmental damage. To date, in Grand Bahama, the impacts of these storms remain evident as many residents still rely on saline groundwater sources, and over 90% of the pine forests have been lost (McKenzie et al., 2023; Welsh et al., 2022; Wilchcombe et al., 2021). As a result of extensive groundwater extraction and altered hydrologic connectivity, many islands have experienced consequences such as aquifer contamination (Frederiks et al., 2024). Some reports also attribute heightened hurricane damage to the soil environment to increased canal dredging, which disrupts natural hydrological barriers on islands (Turner & Ohimain, 2024).

Despite the well-documented consequences of escalating seawater intrusion and soil salinity, a national framework for mitigating these formidable challenges remains to be developed, although the *National Development Plan: Vision 2040* (Office of the Prime Minister, 2017) includes related components that provide a foundation for such a framework. With respect to soil health, the plan calls for a comprehensive framework to prevent and reverse ecosystem loss, including the restoration of degraded land and soil. Regarding freshwater resources, the plan proposes ecosystem valuation studies to assess wetlands, streams, ponds, and estuaries, explicitly linking freshwater ecosystems to agriculture and resource planning. The plan also highlights the importance of mapping flood zones for each island and incorporating water management into broader resilience strategies. While salinity management is not directly articulated, the plan prioritizes coastal protection and integrated coastal zone management strategies, including the restoration of coastal wetlands, construction of both hard and soft coastal defenses, and measures to enhance resilience against flooding and storm surges. These actions are directly relevant to mitigating saltwater intrusion into soils and freshwater lenses.

For The Bahamas to achieve its Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), Climate Action (SDG 13), and Life on Land (SDG 15), urgent action is required to safeguard its fragile soil resources (Lal et al., 2021). Failure to act soon will result in the Bahamas being unable to meet its SDG targets by 2030. Therefore, a cohesive policy framework must align the Bahamas' *National Development Plan* (Office of the Prime Minister, 2017) with strategies to combat soil degradation. Such a framework must address natural vulnerabilities like hurricane-driven storm surges and anthropogenic pressures like groundwater over-extraction. By integrating science-based solutions with adaptive governance, The Bahamas can mitigate saltwater intrusion, preserve soil viability, and secure ecological resilience in the face of worsening climate threats. This paper addresses the current state of groundwater and soil resources in The Bahamas. It proposes management strategies to address the threats and challenges associated with climate change and anthropogenic impacts. The primary objectives are to: (i) summarize current knowledge of groundwater and soil resources, (ii) describe threats associated with climate change, extreme events, and anthropogenic impacts; and (iii) propose strategies to address major salinity threats to groundwater and soils. This paper aims to establish a framework for building resilience to saltwater intrusion into groundwater and soil systems, to support national development goals in The Bahamas.

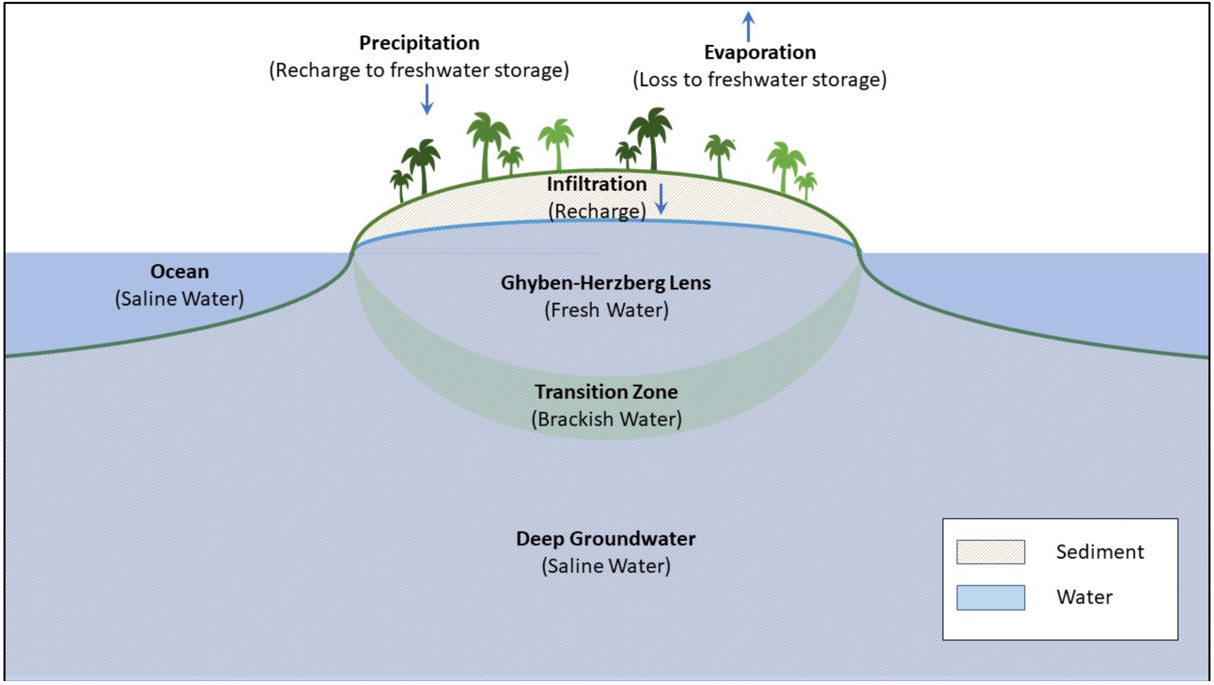
Hydrogeological Overview

Throughout The Bahamas, fresh water found in the subsurface is stored in a freshwater lens, known as a Ghyben-Herzberg Lens, which occurs due to the density difference between fresh and saline water (Cant & Weech, 1986; Bedekar et al., 2019; Tang et al., 2020; see Figure 1). Freshwater lenses are recharged from precipitation, which infiltrates vertically through the soils and sits atop the denser saline water that permeates underneath. Unless physical mixing occurs between the two layers of water, the freshwater lens remains intact. The size of freshwater lenses depends upon climate, geology, the size of the island, and extraction (Bedekar et al., 2019). Freshwater lenses are extremely fragile due to their low quantity of fresh water and threats to their water quality due to human influence and climate change.

The amount of water found in the freshwater lenses varies by island, primarily due to the island size in The Bahamas. The largest island, Andros, has the most extensive freshwater reserves. Grand Bahama and Abaco had the second and third largest reserves, respectively, before Hurricane Dorian. However, following the salinization of the freshwater lens due to the hurricane, the volume of the freshwater lenses on both islands dramatically decreased. No comprehensive quantification of freshwater on the two islands post-Hurricane Dorian has been conducted, although studies have revealed elevated salinity levels remain in groundwater.

Figure 1

Schematic of a freshwater lens in an island setting.



Public drinking water throughout The Bahamas is primarily sourced from these freshwater lenses, in addition to desalinated ocean water. In particular, smaller islands with lower population centres and higher amounts of naturally occurring freshwater supplies utilize groundwater as their source. Larger islands with limited groundwater availability rely on desalination. Some islands blend the two sources; for example, New Providence relies primarily on desalination, with some groundwater supplementation. Certain islands do not have any piped or public water supply for residents, meaning that individuals may rely on personal groundwater wells or, in rare cases, rainwater harvesting. Given the limited amount of fresh water, and specifically groundwater, found throughout the archipelago, this is a fragile resource that needs to be safeguarded. The country is investigating joint water-energy production through processes such as Ocean Thermal Energy Conversion (OTEC), which would allow co-production of water and energy without greenhouse gas emissions (Welsh & Bowleg, 2022).

The development of soil in The Bahamas is closely tied to the unique geological composition of the archipelago, which consists predominantly of young calcium carbonate (limestone) islands. Unlike other Caribbean islands with volcanic or continental origins, the sediments forming The Bahamas are derived from the rich marine life of the banks, accumulating over millennia due to sea-level fluctuations (Whitaker & Smart, 2007; Currie et al., 2019). As a result, Bahamian sediments are rich in fossilized reefs and corals. When these limestone formations are exposed at the surface, they undergo both physical and chemical weathering, leading to the gradual formation of local soils that are characteristically thin (Entisols/Inceptisols), with sandy or loamy textures and high calcium carbonate content, contributing to their high pH, ranging from 7.5 to 8.5 (Wahba et al., 2019; Currie et al., 2019). Given the high porosity of these soils, they have a high drainage capacity and suffer from poor nutrient and water retention. These same traits also heighten their susceptibility to salinization, as rapid leaching promotes the accumulation of soluble salts and limited water retention reduces the soil's capacity to buffer against increases in salinity.

Recent studies on Bahamian soils indicate that they are predominantly sandy in texture, which is expected given the parent material from which these soils are derived. Soils originating from limestone formations tend to exhibit sandy to loamy textures, as they primarily develop from dissolved calcium carbonate, which precipitates as ooliths (Currie et al., 2019; Taylor & Ngatia, 2021). Previous studies have shown soils from Andros and San Salvador Island were mostly sandy or sandy loam (Taylor & Ngatia, 2021; Buehler & Rodgers, 2012). Similarly, a nationwide soil health assessment reported comparable soil textures across six major Islands, including Andros, Berry Islands, Eleuthera, Exuma, Grand Bahama, New Providence, and Ragged Island (Chambers et al., 2023).

The sandy nature of Bahamian soils contributes to their high porosity and low water and nutrient retention. Soil water retention across six islands of The Bahamas ranges from 23% to 44%, which is typical of sandy or sandy loam soils (Chambers et al., 2023). This low water retention capacity influences the soil's ability to retain moisture, particularly during periods of low rainfall. In the southern islands, where rainfall is relatively lower than the northern islands, soil moisture levels tend to be particularly low, leading to prolonged dry conditions and high soil erosion. Foos and Bain (1995) reported that rainfall decreased significantly from 165 cm in the northern islands and 65 cm in the southern islands. Similarly, potential evapotranspiration in the northern islands differs from that in the southern islands; in the northern islands, it is 125 cm, significantly less than the 190 cm observed in the southern islands. This climatic difference in the southern islands results in soils containing pedogenic carbonate nodules and evaporite deposits, which are not present in the northern islands. Similar observations have been reported in other regions with comparable soil textures (Whitaker and Smart, 1997; Cutler et al., 2023). Together, the combination of high evapotranspiration, low precipitation, and limited infiltration reduces recharge to the freshwater lens, further constraining groundwater availability in the southern islands.

In addition to low water retention, Bahamian soils are deficient in essential nutrients. A comparative study analyzing soils from six major islands found that nitrogen levels varied significantly (Chambers et al., 2023), with some sites exhibiting levels above the optimal range due to improper use of fertilizers, while others were deficient. Phosphorus concentrations were consistently above the optimal range in all samples, whereas potassium was deficient in nearly all samples, with only one site meeting the optimal threshold. Another study on Andros Island found that its soils exhibited low phosphorus concentrations, high calcium levels, and normal potassium concentrations (Taylor & Ngatia, 2021). These nutrient imbalances directly limit crop productivity and necessitate careful soil management strategies.

Although the vast majority of soils in The Bahamas are sandy to sandy loam, other soil types, such as organic and lateritic, have also been observed. The primary organic soils in The Bahamas include leaf mold and muck soils, which are low in mineral nutrients. Leaf mold soils primarily form on flat, rocky lands of larger islands such as Andros, Abaco, Grand Bahama, and New Providence (Foos & Bain, 1995). They consist of a thin humus layer overlying humic sandy earth, whereas muck soils are thicker and typically found in hollows prone to periodic flooding. An example of where such soils accumulate is in banana holes, unique karst features found throughout The Bahamas. These natural depressions facilitate the formation of muck soils, contributing to localized fertility in an otherwise carbonate-dominated landscape, since such soils have low nutrients and water holding capacity, making them unsuitable for most crops (Breithaupt et al., 2022).

Lateritic soils in The Bahamas are thin and discontinuous and develop on lithified Pleistocene deposits, primarily on San Salvador and Eleuthera. They form through the accumulation of insoluble alumina-silicates and iron oxides, which are transported by trade winds from North Africa as airborne dust (Muhs et al., 2007). These soils are rich in hematite, goethite, boehmite, and hydroxy-interlayered clays, with low silicon dioxide (SiO_2) to aluminum oxide (Al_2O_3) ratios, indicating advanced chemical maturity. It should be noted that highly mature soils have lost many base cations and nutrients during prolonged weathering, and they provide limited fertility for agriculture. They occur in shallow solution depressions on eolian ridges and exhibit high permeability, leading to poor moisture retention and a tendency to dry out between rainfall events. Their distinct reddish-brown colour results from iron oxide accumulation and contributes to the pedogenic alteration of carbonate surfaces (Foos, 1991; Foos & Bain, 1995).

Given the fragile and limited nature of Bahamian soils, they are particularly vulnerable. Mostly, these soils are already classified as poor in terms of fertility and structure, making them highly susceptible to climate change. The island's limestone composition, combined with climate change-induced sea level rise, hurricanes, and shifting rainfall patterns, put them at risk of saltwater intrusion.

Challenges and Threats

Water availability and access are issues globally, with numerous threats leading to water scarcity, although SIDS worldwide are particularly vulnerable to these issues. The primary threats to water availability include pressures due to climate change, including reduced precipitation to recharge the groundwater and salinization of the freshwater lens, and over-extraction of freshwater for human consumption. Additionally, water quality in freshwater lenses is threatened by anthropogenic activities on land, such as development and contamination (Welsh & Bowleg, 2022).

Soil degradation, defined as the decline in soil health that compromises its ability to provide essential ecosystem services such as nutrient cycling, water filtration, and carbon storage, is a global issue, and SIDS like The Bahamas are particularly vulnerable. This growing crisis threatens agricultural productivity and freshwater quality, making it a critical environmental and socio-economic concern. The soil resources of the Bahamian archipelago face mounting pressures from both natural and anthropogenic activities. These threats include soil salinization, erosion, organic matter loss, contamination driven by rapid urbanization, unsustainable land use, and extreme weather events.

Threats of Climate Change

The impacts of climate change on the hydrology of The Bahamas are multifaceted, causing substantial effects on soils and freshwater resources. Climate change can alter precipitation patterns, cause sea level rise, and affect the occurrence and magnitude of extreme weather events, including droughts, flooding, and hurricanes. Shifting precipitation patterns can impact the timing of the rainy and dry season, the amount of precipitation that falls, and the intensity of precipitation (Rolland et al., 2014). These changes alter infiltration and groundwater recharge rates, directly affecting the freshwater lens size (Bedaker et al., 2019). For example, a prolonged dry season can mean that the freshwater lens cannot be recharged sufficiently to address the needs of those who rely on that water for public water supply. With stronger rain events, flooding can occur if soils are overdried or if they are oversaturated due to previous rain events.

In addition, due to changing climate patterns across the globe, sea level rise is a growing concern for low-lying islands, including The Bahamas. Globally, the sea level has risen by an average of 18.15 cm over the last 145 years (Lindsey, 2023). This is particularly worrisome for low-lying island nations like The Bahamas, where over 80% of the landmass is less than 10 m above sea level. The Bahamas is expected to experience a sea-level rise of 25.01 cm in the next 20-25 years, which will have serious consequences for its limited soil resources (Martin del Campo et al., 2023). Studies indicate that sea levels rose by 10 cm over 75 years in Andros Island (Wu et al., 2021).

Saltwater intrusion accompanies sea level rise, which moves the interface between subsurface saltwater and freshwater further inland in coastal regions (Bedaker et al., 2019; Ketabchi et al., 2016). This shift in the interface directly reduces the volume of freshwater that is available for human use. Climate change has also led to an unprecedented increase in saltwater intrusion in arid soils. This increasing frequency of saltwater intrusion leads to a rise in soil salinity, alkalinization, and sulfidation, all devastatingly affecting soil health. Results from Grand Bahama reported that the average soil salinity across the two primary wellfields that supply potable water to the island was 475.5 mg/kg in 2022 (Welsh et al. 2022; Stubbs et al., 2023). Another study from Andros found soil salinity levels as high as 2,450 ppm (Taylor & Ngatia, 2021). Long Island also reported similar results when soils were amended with seaweed. Increased soil salinity results in high osmotic stress, restricting plant water and nutrient availability, ultimately reducing crop yield. Studies have also shown that plant growth is significantly inhibited in saline soils due to reduced growth in root tips and young leaves, leading to decreased photosynthesis (Adderley et al., 2023). This increase in soil salinity negatively impacts seed germination and ultimately reduces agricultural productivity.

Historically, hurricanes have caused significant devastation to soils and groundwater resources throughout The Bahamas. As the frequency and intensity of hurricanes increases as a result of climate change, the country is at even more risk. In particular, storm surges and flooding cause seawater inundation onto land, resulting in saltwater intrusion into the freshwater lens and salinization of terrestrial soils, including forested areas around wellfields and agricultural lands (Holding & Allen, 2015).

One primary example of the impact of hurricanes is in Grand Bahama, which suffered extreme salinization of its freshwater lens and soils due to Hurricane Dorian. As the island with the second largest naturally occurring freshwater resources, Grand Bahama relied on groundwater for its public water supply. However, during Hurricane Dorian, flooding reached up to 21 feet (6.4 m) in some portions of the island, and the flood waters remained over several days (see Figure 2a-b; Welsh et al., 2022). This extreme flooding inundated the groundwater, effectively destroying the freshwater lens and resulting in the inability to use groundwater for potable water sources. Additionally, when the floodwaters receded, silts and clay-like material settled out, causing crusting and a claypan layer with elevated levels of salinity and contaminants bound in the soils, impacting the infiltration of precipitation into the subsurface and affecting the quality of the water that did infiltrate. Post-hurricane assessments have revealed elevated salinity levels in groundwater and soil, underscoring the impact of hurricanes on hydrogeological resources (Welsh et al., 2022).

Figure 2

Satellite imagery illustrating landscape changes in Grand Bahama Island before and after Hurricane Dorian.

Note: Panel (a) shows conditions before the hurricane (January 2019), while panel (b) captures the extensive flooding and damage in the immediate aftermath (September 2019). Sources: Google Earth (a) and ICEYE (b).

The impact of saltwater intrusion has become more frequent in recent years as The Bahamas has experienced increasingly extreme hurricanes, resulting in widespread soil flooding with seawater. Throughout the southern islands, post-storm vegetation die-off near the coast is evident in many areas flooded with seawater. Furthermore, saltwater intrusion leads to soil alkalinization, causing sodium accumulation that alters soil structure, clogs pores, and impairs water infiltration and drainage (Su et al., 2025). After Hurricane Dorian, large areas of clay-like material with high soil salinity concentrations were observed in regions flooded with seawater. This clogged the pores and restricted water movement, further exacerbating soil degradation. These conditions disrupt nutrient dynamics by promoting the desorption of essential nutrients like ammonium, increasing the risk of nutrient imbalances and leaching. Additionally, under persistent saltwater intrusion conditions, microbial sulfate reduction produces hydrogen sulfide, a toxic compound that inhibits plant growth and alters plant community composition. Lastly, sulfidation affects phosphorus cycling by making iron unavailable to bind phosphate, leading to elevated phosphorus levels in water systems (Medellín-Azuara et al., 2014; Su et al., 2025).

Anthropogenic Threats

Extraction of groundwater for human use is one of the most significant threats to the availability of freshwater resources, particularly for small island nations. As The Bahamas lacks any major source of surface water that contains fresh water, the only natural source of potable water for extraction is in the freshwater lens. However, fresh water faces increasing demand in The Bahamas due to a growing population, intensified development, and water-intensive activities accompanying tourism. Extraction of water from the freshwater lens causes a reduction in the size of the lens, which can only be reversed by increased recharge from precipitation. Therefore, when extraction from the freshwater lens exceeds recharge, saltwater infiltrates the subsurface.

Saltwater intrusion has occurred throughout the country, with one case study in New Providence. Groundwater served as the primary source of potable water for the island historically until over-extraction caused the salinization of the wellfields, and the island was required to rapidly shift to water barged in from Andros to meet the demand of the island and then later shifted to desalination (Welsh & Bowleg, 2022). Following the abandonment of those wellfields, the freshwater lens still has not fully recovered several decades later.

While several islands have shifted towards desalination of ocean water, this method for water provision has notable challenges for small islands. Establishing new facilities requires significant investment and resources that tend to be lacking in small island nations. Additionally, desalination is extremely energy intensive, requiring large amounts of fossil fuels and significant economic costs for operation, as well as creating greenhouse gas emissions that contribute to climate change (Cornejo et al., 2014). The toxic brine sludge waste that is created in the process of desalination also poses disposal challenges and threatens the environment in locations where it is deposited.

In addition to natural threats, Bahamian soils face numerous anthropogenic threats, including land use pressures, poor agricultural practices, pollution, and waste management. Since independence, The Bahamas has experienced rapid urbanization, primarily in the nation’s capital, where over 80% of the population resides in urban areas (Mycoo, 2022). This increase in urbanization puts significant pressure on soil resources and exacerbates the loss of available soil. Studies have shown that soils face increased degradation as cities expand due to soil sealing, which prevents natural soil processes. Sealed surfaces block water infiltration, reducing groundwater recharge and increased runoff, exacerbating erosion and flooding. Additionally, soil compaction from urban development reduces aeration and microbial activity, further impairing soil structure and biodiversity (Vieillard et al., 2024; O’Neill, 2015). Similarly, during home construction in The Bahamas, the topsoil is often removed to expose the limestone bedrock to ensure a stable foundation. While this practice provides structural stability, it significantly contributes to soil loss and threatens soil sustainability. Moreover, instead of replacing the removed topsoil, properties are frequently filled with “corey/fill” material made from crushed limestone.

In addition to soil sealing and removal of top soils, increasing urbanization has resulted in widespread land clearing for development, leading to massive deforestation. Recent reports indicate that The Bahamas has lost a significant proportion of its forest cover. A recent study reported that between 2004 and 2020, urban expansion and development led to the loss of approximately 555,392 pine trees in the Grand Bahama pine forest (McKenzie, 2024). Similarly, New Providence has undergone extensive pine forest loss, with approximately 339 out of 786 acres cleared in the Carmichael Road area (see Figure 3a-c). These instances of deforestation have also been reported on other islands. Studies have shown that deforestation significantly reduces soil organic matter (SOM), essential for soil fertility and quality. Deforestation's loss of plant cover and litter decreases SOM levels, leading to increased soil erosion, reduced nutrient availability, and enhanced leaching of essential cations. Soil physical properties, such as texture and porosity, are also negatively impacted, increasing sand content and bulk density, making the soil more prone to drought and erosion. Microbial activity and biomass decline in deforested soils due to the loss of organic material inputs, which are crucial for sustaining microbial communities and enzyme activities (Stubbs et al., 2023; Chambers et al., 2023).

Figure 3

Forest cover dynamics from 2000 through 2022 in the Carmichael area.

Note: Panels (a), (b), and (c) correspond to satellite imagery from the years 2000, 2014, and 2022, respectively. Images illustrate the progressive loss of forest cover over 22 years (source: Google Earth).

Illegal charcoal production using pine and other native plants in The Bahamas also negatively impacts soil health. Recently, numerous news reports of charcoal production, particularly in the Carmichael Road area, have surfaced. The process primarily involves carbonizing aboveground tree biomass using traditional kilns, such as pit kilns and earth-mound kilns. While pit kilns are dug into the ground and covered with leaves and soil to control combustion, earth-mound kilns are built above ground and covered with organic material and soil. The extreme heat from charcoal kilns alters soil properties, reducing bulk density while increasing porosity and infiltration rates. This decreases soil fertility by disrupting soil aggregates, reducing water retention, and increasing erosion risks (Oguntunde et al., 2008).

Another major threat to soil health in The Bahamas is pollution from illegal dumping and the burning of scrap metal. Dumping old appliances and construction waste on vacant lands has become a common practice (Wosnick et al., 2024). This form of illegal dumping, which has been reported across The Bahamas, poses a serious threat to soil health. This practice introduces hazardous materials, altering soil structure and disrupting natural processes. Appliances often contain heavy metals, plastics, and toxic chemicals that leach into the soil, contaminating it and reducing its quality. Construction waste, such as concrete, bricks, and insulation materials, can compact the soil, reducing water infiltration and aeration, negatively affecting plant growth and microbial activity (Kader et al., 2024). Additionally, the accumulation of non-biodegradable materials disrupts nutrient cycles and can lead to long-term soil degradation. The burning of e-waste further deteriorates soil health. Studies have shown that e-waste dismantling significantly degrades soil by introducing heavy metals and organic pollutants. These activities release hazardous elements such as lead, copper, and antimony from electronic components. In contrast, burning plastics releases harmful organic compounds like polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and polybrominated diphenyl ethers, further contaminating the soil. A recent study highlighted that e-waste is becoming a growing environmental challenge in The Bahamas, with inadequate regulations exacerbating the issue (Wosnick et al., 2024).

Improper fertilizer application is another threat to soil health and water quality. Excessive use of chemical fertilizers depletes soil organic matter, reduces overall soil fertility, and causes increased nutrient loading to water bodies. Continuous application alters soil pH, leading to acidification and making the soil less suitable for plant growth. Over-reliance on fertilizers weakens microbial activity, disrupting soil biodiversity. A recent comparative analysis of soil health in backyard farms across several Bahamian islands found that none of the 38 soil samples analyzed fell within the optimal range for selected indicators, with some samples having nitrate concentrations well above permissible levels. While natural fertilizers are generally considered beneficial for soil health, certain types can have adverse effects (Chambers et al., 2023). For instance, a study conducted on Long Island investigated the use of Sargassum species as a biofertilizer (Adderley et al., 2023). The findings revealed that although Sargassum application increased soil nutrient content, it negatively impacted plant growth performance.

Strategies to address fresh water and soil salinity

Natural Strategies

After experiencing saltwater intrusion into the freshwater lens, natural recovery through rainfall recharge can take an extensive period of time, from months to decades or longer. This natural regeneration process can be lengthy, particularly due to low rainfall or high extraction from the freshwater lens. Frequently, water managers will abandon compromised groundwater resources, such as in New Providence (Welsh & Bowleg, 2022). Therefore, engineered recovery strategies have been more commonly implemented to address extreme salinization of groundwater.

Halophytes are specialized plants adapted to survive in saline environments and are valuable for remediating salt-affected water and soils. These plants possess a range of physiological and morphological adaptations that enable them to tolerate high salinity through salt exclusion, excretion, and accumulation. By actively absorbing salts, particularly into their leaves, halophytes help reduce soil salinity, alleviate osmotic stress, and improve soil structure and fertility (Hasanuzzaman et al., 2014). Species such as *Suaeda maritima* and *Sesuvium portulacastrum* have been widely studied and shown effective in salt remediation. Their ability to remove significant amounts of salt from the soil makes them ideal candidates for restoring saline-impacted land to productive use. This salt-absorbing capacity also facilitates vegetation regrowth and supports ecological restoration in areas severely affected by saltwater intrusion due to storm surges, hurricanes, or excessive agrochemical inputs (Zhang et al., 2024; Hasanuzzaman et al., 2014). Although documented cases of halophyte application following hurricanes in The Bahamas are limited, several species demonstrate clear potential. For instance, *Salicornia bigelovii* has been explored for its soil desalination capacity, while *Atriplex* species are recognized for improving soil structure and fertility under saline conditions (Zhang et al., 2024, Wang et al., 2023; Hasanuzzaman et al., 2014). These species could prove useful in post-hurricane restoration efforts across the region and conducting pilot studies on halophyte remediation would provide useful information as to its feasibility.

Organic amendments, including compost, green manures, and crop residues, further enhance soil health by restoring organic matter. Amendments such as compost, farmyard manure, green manures, and crop residues contribute to increased organic matter content, enhancing soil fertility and structure while boosting microbial activity. These amendments promote aggregate stability, lower bulk density, increase aeration, and enhance water retention, creating conditions conducive to root growth and microbial colonization (Tao et al., 2024). Similarly, they raise soil organic carbon levels and cation exchange capacity, improving nutrient retention and availability (Bashir et al., 2021). Furthermore, the organic material provides substrates that stimulate microbial biomass and enzymatic processes and facilitate nutrient cycling. These improvements in soil structure will decrease soil salinity (Soria et al., 2021; Tao et al., 2024).

Engineered Strategies

Artificial recharge methods can expedite the slow natural recovery of freshwater lenses and include injecting fresh water back into the freshwater lens. For example, damaged freshwater lenses or saline water could be extracted from the subsurface, treated with a portable reverse osmosis system, and reinjected into groundwater. Another option is managed aquifer recharge (MAR), which uses a supplemental source of freshwater and artificially recharges the aquifer. MAR has been implemented in other locations worldwide (see Imig et al., 2022) but with limited implementation in small islands due to the lack of sources of supplemental freshwater. For example, rooftop rainwater harvesting systems can capture rainfall, which can be directly injected into the freshwater lens (Imig et al., 2024). However, a recent cost-benefit analysis of MAR implementation in Grand Bahama post-Hurricane Dorian estimated that the costs of this mechanism exceed the potential benefits (Imig et al., 2024). Therefore, this may not be a viable solution for small islands like the Bahamian archipelago.

Flushing and leaching are widely used methods for reducing salt concentrations in soils affected by seawater inundation. Flushing involves the application of large volumes of clean water to dissolve and wash away surface salt crusts, which are particularly effective in fine-textured soils. Leaching entails using excess irrigation water to move soluble salts beyond the root zone, provided proper drainage systems are in place to prevent upward salt migration through capillary rise (Stavi et al., 2021).

These practices lower salt concentrations in the rhizosphere, enhancing water uptake and reducing sodium-induced root stress. However, leaching must be managed carefully. Excessive water application can wash away beneficial cations like calcium and magnesium, which may lead to increased sodicity if sodium remains dominant in the soil solution. Unlike salinity, which results from the overall accumulation of soluble salts and primarily affects plants through osmotic stress, sodicity refers to the excessive presence of sodium on soil exchange sites, causing clay dispersion, reduced infiltration, and structural degradation (Stavi et al., 2021). Similar to MAR, this option is challenging with limited available fresh water.

Monitoring and Adaptive Management

A lack of historic soil and groundwater data throughout The Bahamas is a current challenge for tailored management of natural resources. For example, comprehensive Bahamian hydrology studies are limited to a study conducted in 2004, by the U.S. Army Corps of Engineers. As no comprehensive study quantifying freshwater volume has been conducted throughout The Bahamas since the U.S. Army Corps of Engineers 2004 study, an updated study that evaluates present-day conditions following these hurricanes is necessary for effective management of water resources. More current data are needed at a finer spatial resolution to quantify the amount of water available in the freshwater lens, depth to the groundwater table, and precipitation rates. In addition, updated soil data on texture, structure, and salinity are necessary to evaluate water retention and recharge potential.

Moving forward, we can address these shortcomings by establishing robust, real-time monitoring networks of groundwater that measure water quality parameters, such as salinity, at a frequent time scale multiple times a day. This increased frequency will allow for measuring the impact of individual rain events or storms on groundwater water quality. Additionally, real-time water quality monitoring at the boundary of the freshwater lens would allow for advanced warning of saltwater intrusion occurring laterally due to rising sea levels, which would enable management efforts, such as reducing extraction rates, to address the threat immediately.

Establishing flexible management plans that can adapt to changing effects is critical for addressing issues that are identified from more frequent data monitoring, as well as emerging issues that may arise. For example, if water sensors in groundwater wells identify saltwater intrusion through increasing salinity levels, freshwater extraction can be slowed or halted. Plans for extreme events, including hurricanes, are essential for addressing the impacts immediately and identifying alternative water sources during recovery efforts.

Diversifying water sources is essential for all islands, but particularly for those islands that rely on only one source. Hurricane Dorian was a prime example of the difficulties that arise when one water source, in this case groundwater on Grand Bahama, is significantly impacted. In that instance, the freshwater lens was inundated with salt water, rendering groundwater no longer safe for human consumption. A portable reverse osmosis system was implemented for water provision, drawing on the saline groundwater. However, this continued groundwater extraction does not allow for natural recovery of the freshwater lens.

Involving the multitude of individuals who influence water management is critical, such as decision-makers, government officials, and in-country water managers, including organizations, such as the Water and Sewerage Corporation, Grand Bahama Utility Company, New Providence Water Development Company, the Bahamas Department of Meteorology, and the Ministry of the Environment. Additionally, these organizations can collaborate to ensure effective communication between individuals responsible for managing water and soil resources. Data is currently safeguarded by organizations, which makes research and management into these issues very challenging. Creating open-access data-sharing platforms would improve understanding of our resources and promote sound science; for example, the SwissEnvEO Spatial Data Infrastructure in Switzerland implements a national-scale, satellite-derived Earth observation data cube with “ready-to-use” environmental products that fully comply with Findable, Accessible, Interoperable, and Reusable (FAIR) principles, offering a strong precedent that the Bahamas could adapt (Giuliani et al., 2021).

Monitoring soil salinity is critical in managing the growing threat of saltwater intrusion, especially in low-lying island nations like The Bahamas. Given the archipelago’s fragile soils and increasing exposure to hurricanes and storm surges, it is important to have systems that can track changes in soil salinity over time. While traditional field-based approaches, like collecting soil samples and testing for electrical conductivity and moisture content in the laboratory, are still the most accurate, these methods are often slow, costly, and difficult to carry out on a large scale (Corwin & Lesch, 2005). Newer technologies, such as satellite and drone-based remote sensing, are making monitoring soil salinity easier across wide areas. These tools use vegetation and soil reflectance patterns to detect salt buildup, often relying on indices like the Normalized Difference Vegetation Index or Normalized Difference Salinity Index to detect problematic areas (Salem & Jia, 2024). When paired with ground measurements and advanced data analysis techniques to support vector machines or random forest models, these approaches can provide a clearer overview of where salinity issues are emerging and how they are changing. However, no single method works everywhere, and models need to be calibrated to local conditions, especially given the unique soils and climate of The Bahamas. To move forward, The Bahamas would benefit from building a national monitoring system that blends these tools, on-the-ground sensors, remote imagery, and predictive modeling. Such a system would support timely interventions, help guide recovery after storms, and inform long-term strategies to protect soil and water resources.

Conclusion

The Bahamas faces increasing threats to its freshwater and soil resources due to saltwater intrusion driven by climate change, sea level rise, and human activity. This manuscript highlights the archipelago's unique hydrogeological and pedological characteristics, emphasizing how these factors make the country especially vulnerable to salinization and resource degradation. By examining natural and anthropogenic pressures, the study provides a clear overview of the current challenges and proposes a framework for improving resilience through integrated soil and water resource management. Key threats identified include rising sea levels, intensifying storm surges, prolonged droughts, over-extraction of groundwater, deforestation, and poor land use practices, compounding the vulnerability of The Bahamas' already fragile ecosystems. The framework outlined in this paper includes natural and engineered strategies, such as managed aquifer recharge, halophytes, organic amendments, and improved salinity monitoring systems. To build long-term resilience, national planning must incorporate adaptive management approaches, enhanced data collection, and proactive restoration efforts aligning with national and Sustainable Development Goals. To that end, we recommend the following actions for water resource managers in The Bahamas:

1. Focus on natural and engineered strategies for salinity mitigation in fresh water and soils.
2. Seek alternative water sources, such as desalination and rainwater harvesting, and reduce groundwater extraction to facilitate natural recovery of the freshwater lens.
3. Implement programs that focus on mitigating soil salinity and improving overall soil health.
4. Develop a real-time monitoring network for soil and groundwater salinity and incorporate data into predictive modeling that will provide advance warning of threats to the soil and groundwater.
5. Implement a national strategy to ensure that all data collected is shared, open access, and available for use.
6. Promote community involvement in the development and implementation of monitoring plans.

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