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The Bahamas at risk

Material stocks, sea-level rise, and the implications for development

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Abstract

Recent research suggests that over 75% of resources extracted globally now go toward creating, maintaining, or operating material stocks (MS) to provide societal services like housing, transport, education, and health. However, the integrity of current and future built environments, and the capacity of the system to continue providing services, are threatened by extreme events and sea-level rise (SLR). This is especially significant for the most disaster-prone countries in the world: Small Island Developing States. In the aftermath of disasters, complex rebuilding efforts require substantial material and economic resources, oftentimes incurring massive debt. Understanding the composition and dynamics of MS and environmental threats is essential for current and future sustainable development. Drawing on open-source OpenStreetMap (OSM) data, we conducted a spatially explicit material stock analysis (MSA) for The Bahamas for 2021, where we included buildings and transport MS, and SLR exposure scenarios. Total MS was estimated at 76 million tonnes (Mt) or 191 tonnes per capita (t/cap) of which transport comprises 43%. These MS are likely to increase by 36 Mt in the future. Simulations show that under 1-, 2-, or 3-m SLR scenarios, around 4, 6, and 9 Mt of current MS will be exposed, with transport MS at greatest risk, with over 80% of total exposure in each scenario. Our findings highlight the critical role that key MS play in sustainability and resilience, contributing to the emphasis on effective development planning and climate change adaptation strategies, and to the exploration of the use of OSM data for studying these objectives.

KEYWORDS

industrial ecology, island sustainability, material stock analysis, OpenStreetMap, sea-level rise, socio-metabolic risks

1 | INTRODUCTION

Between 1970 and 2010, global material extraction of construction materials has shown a five-fold increase, far exceeding population growth, leading to a considerable increase in material-use per capita (UNEP, 2016). In 2015, 75% of all materials extracted globally (62 Gt/year) were either used to build-up stocks or to operate them to provide societal services (Krausmann et al., 2020). Stocks are drivers for resource flows required for their construction, use, or maintenance, finally resulting in waste outflows and emissions. These elevated and still growing rates of

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material-use come at the cost of exploitation of unevenly distributed and limited construction material resources, posing major threats to global and local sustainability.

In the Caribbean Small Island Developing States (SIDS), growth in infrastructure is of special significance, considering the impacts of sea-level rise (SLR) and extreme events, which are increasing both in frequency and intensity (CRED & UNISDR, 2018; Mycoo et al., 2022). These result in material losses and in the immediate loss of critical services, and restoring these services requires significant resources for reconstruction, which oftentimes need to be secured by incurring huge debts (Alleyne et al., 2022). Caribbean SIDS population has increased by 15% since 2000, from 6.5 to 7.4 million in 2020 (The World Bank, 2022a), while average urban development reached 50% in 2020 (The World Bank, 2022b). Caribbean SIDS continually rank among the top 30 countries regarding exposure and vulnerability to risks (Aleksandrova et al., 2021). The region has been affected by more than 40 storms (including 11 Category 4 and 5 hurricanes) between 2000 and 2021, affecting more than 25 million inhabitants. In 2017, Hurricane Maria and Hurricane Irma caused live losses and massive widespread infrastructure damages amounting to almost USD 90 billion, surpassing the cumulative USD 71.7 billion GDP of the Caribbean SIDS in that same year (EM-DAT & CRED, 2022; OCHA, 2020; The World Bank, 2020).

Buildings and infrastructure stock analysis have been performed through the application of material stock and flow analysis approaches at different spatio-temporal scales (see critical reviews from Fu et al., 2022; Lanau et al., 2019; Nasir et al. 2021). Most recently, the combination of geospatial data and socioeconomic data with statistics on material stocks (MS) (Heeren & Hellweg, 2019; Tanikawa et al., 2015) has advanced our understanding of MS dynamics. A small number of MS studies have applied freely and openly available geospatial data (OpenStreetMap, OSM) on their approaches (Deetman et al., 2021; Haberl et al., 2021; He et al., 2020; Inostroza et al., 2019; Klooststra, 2021; Miatto et al., 2021; Rousseau et al., 2022; Thunshirn, 2020). Few others have investigated MS at risk from natural disasters (Gallardo et al., 2014; Kahhat et al., 2017; Tanikawa & Sugimoto, 2016; Tanikawa et al., 2014), while fewer have had small islands as the study area (Bradshaw et al., 2020; Merschroth et al., 2020; Symmes et al., 2019; Ye, 2022). SLR threatens vital infrastructure, settlements, and facilities that support the livelihood of island communities, especially those of low-lying territories (The World Bank, 2017). Information on MS patterns and drivers of risks in these highly dynamic coastal zones is essential for current and future development.

In this study, we conducted an economy-wide Geographical Information System (GIS) bottom-up material stock accounting (MSA) analysis for The Bahamas for 2021. We focus on estimating current and future MS and their exposure to SLR. Specifically, we focus on the MS of: (a) buildings, and (b) transport infrastructure. We expand on the MSA analysis and bring new interesting insights by identifying MS patterns that influence the system's exposure to risks and that could impact over near-future and long-term development. This study will inform about potential directions of future resilience-development strategies in the country. We address these research questions: What is the current composition of MS in The Bahamas and where are they located? What are the expected evolution of MS and future material requirements? How do SLR scenarios impact current MS and future development? We draw on OSM data to compensate for the lack of fundamental information from formal sources about buildings and infrastructure stock. We also discuss the challenges and potentials of this approach.

2 | THE COMMONWEALTH OF THE BAHAMAS

The Bahamas is the largest small-island archipelago in the tropical Atlantic Ocean by area. Comprising over 700 low-lying islands and cays, it has a total internal land area of around 14,000 km² (The Bahamas Protected Area Fund, 2020) of which 80% is less than 10 m above sea level (Reguero et al., 2015). The population was around 400,000 as of 2021 (Worldometer, 2022), with 70% of it living on two islands: New Providence and Grand Bahama (Government of The Bahamas, 2012). Tourism and tourism-driven activities represent 60% of GDP and, directly or indirectly, employ half of the archipelago's labor force (IBRD, 2021).

The Bahamas has been identified as one of the Caribbean countries most exposed to climate change and storm surges (EM-DAT & CRED, 2022; Silver et al., 2019; Simpson et al., 2010). These climate change-related threats put at risk significant portions of the built and natural environment, and economy of The Bahamas (IDB, 2022b; Silver et al., 2019; The Bahamas Environment, Science and Technology (BEST) Commission, 2005). These events have resulted in the loss of lives, severe flooding, and disastrous damage to transport, housing, power infrastructure, and complex post-disaster rebuilding efforts, which in some instances has not yet recovered (Deopersad et al., 2020; Bello, Hendrickson et al., 2020).

The Government of The Bahamas has identified key vulnerabilities that threaten the overall sustainability of the country. These include a highly vulnerable natural and built environment, and a highly vulnerable, undiversified, and underperforming economy, with inadequate housing, and community infrastructure, deficient long-term infrastructure planning, and a lack of preparedness for inevitable climate change (Government of The Bahamas, 2016b). The analysis of a new island case study with these characteristics represents an opportunity to better understand the dynamics between in-use MS, resource requirements, and risks arising from SLR.

3 | METHODS

To analyze current buildings and transport stocks, future material requirements, and potential impacts of SLR, we conducted a GIS-based MSA for 2021. The study area was the political boundary of The Bahamas. Estimations were derived using the ArcGIS Pro 2.8.3 software.

3.1 | Stocks of buildings

The general approach in calculating these is to categorize the building inventory into distinctive use-types or typologies, calculate the gross floor area (GFA), apply material intensities (MI) for each typology, and calculate total MS for four main construction materials: aggregate, concrete, timber, and steel. During the building classification process, the November 2021 building footprint shapefile layer (sourced from OSM) and extracted through the Humanitarian Data Exchange project (HOTOSM) (Humanitarian OpenStreetMap Team, 2021a), was used as a base data.

We classified the existing building footprints into five main typologies: residential, commercial, industrial, government, and other (seaports and airports buildings were included under transport). A small fraction (around 20%) of the 117,000 building footprints from the OSM shapefile layer already had a clear classification into different typologies. We interpreted satellite imagery and associated the remaining uncertain building footprints with nearby known buildings based on size and layout, and extra information within the OSM shapefile layer (see Supporting Information S1). This allowed us to allocate distinct MI values (in kg/m²) for these main typologies. GFA (in m²) for each individual building “*b*” was calculated through estimating the individual building footprint area_(b) and multiplying it with its corresponding number of stories_(b).

$$\text{GFA}_{(b)} = \text{Building footprint area}_{(b)} \times \text{Number of floor stories}_{(b)} \quad (1)$$

Material stock “MS” was calculated for each of the main material categories “*m*” and for each individual building “*b*” by multiplying “GFA_(b)” by its corresponding “MI_(m).”

$$\text{MS}_{(b,m)} = \text{GFA}_{(b)} \times \text{MI}_{(m)} \quad (2)$$

Deficiencies in data availability for MI (e.g., no previous studies, no access to building footprints or bill of materials) did not allow for the estimations of MI specifically for The Bahamas. To cover that gap we explored the census of population and housing (Government of The Bahamas, 2012), and the household expenditure survey (Government of The Bahamas, 2016a). We consulted previous publications with information on the building typologies of other Caribbean SIDS, namely Grenada (Symmes et al., 2019) and Antigua and Barbuda (Bradshaw et al., 2020).

In Grenada, few older traditional buildings are composed of brick and stone, with tile roofs. Recently, there has been a change in typical building structures. As new construction materials became more available and cheaper (like cement and glass), there was a dramatic increase in their use, replacing wood with concrete (Saunders, 2016). Based on Grenada’s census data, around 52% of the outer wall material for housing is concrete dominant (Alam, 2015), while wood represents close to 47% (IDB, 2022a).

In Antigua and Barbuda, most of the historic buildings in the capital city of St. John have a lower floor structure of masonry construction and the upper floor of timber wood. Further, timber-framed buildings are still relatively common, but to a lesser degree. Many of the oldest small buildings and homes are fully timber framed and timber clad. Masonry and mortared rock wall construction is the most common building type and the dominant construction type for residential and other small buildings, including most of the public sector building portfolio (GovAB, 2019; UN-HABITAT, 2011). For Antigua and Barbuda, the overall composition of the outer wall materials is 40% concrete and 59% wood (IDB, 2022a).

In comparison, the latest census in The Bahamas shows that most dwellings are built on concrete blocks structures (80% of all outer walls), with poured concrete slabs and concrete foundations (90% of all floors). The most common roofing materials are asphalt shingles (90%) and corrugated metal sheets (4%) (Government of The Bahamas, 2016a). This construction style can be largely seen across New Providence and Grand Bahama, and to a slightly lesser extent, in the Family Islands. Wood and timber constructions as main structural components are also in use, but with lower numbers (ECLAC, 2020). As The Bahamas’ building typologies share more similarities with Grenada’s buildings (concrete dominant) than with Antigua and Barbuda (timber dominant), we opted to utilize the MIs described in Symmes et al. (2019). See Table 1 with MIs for buildings and transport stocks.

Total material stock “MS_{total}” per main material category and for a building “GFA_(b)” was calculated as follows:

$$\text{MS}_{\text{total}} = \sum \text{MS}_{(b,m)} = \text{MS_Aggregate}_{(b,m)} + \text{MS_Timber}_{(b,m)} + \text{MS_Concrete}_{(b,m)} + \text{MS_Steel}_{(b,m)} \quad (3)$$

To calculate total MS per building typology, Equation (3) is applied for each of the five typologies (see Table 2).

TABLE 1 Material intensities allocation for buildings and transport stocks. Units as indicated. *Sources:* Government of The Bahamas (2004), Symmes et al. (2019), U.S. Department of Transportation (2016). Note that concrete is a composite material. A differentiation of main materials was made based on structural components. The assumption of taking Grenada's MIs as valid for the buildings in The Bahamas, as well as the Airport Pavement Design and Evaluation guidelines for seaport platforms and airport runways material intensities, affects the ability to reduce uncertainties on material stocks estimations. As such, it is advised that these should be considered with a degree of caution due to inconsistencies in data collection methodologies and completeness

Buildings	Aggregate	Timber	Concrete	Steel	Typology
Concrete structure (kg/m ²)					
Foundation—Strip footings	135	0	225	5	Residential (85%) Commercial Government
Foundation—Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	0	520	1	
Roof—Frame	0	40	0	0	
Roof—Covering	0	0	0	10	
Total	159	40	1645	36	
Timber structure (kg/m ²)					
Foundation—Pad footings	45	0	45	1	Residential (10%) Other
Foundation—Posts	0	0	300	5	
Floors	0	0	0	20	
Walls	0	50	0	0	
Roof—Frame	0	40	0	0	
Roof—Covering	0	0	0	10	
Total	45	90	345	36	
Concrete/timber mix structure (kg/m ²)					
Foundation—Strip footings	135	0	225	5	Residential (5%)
Foundation—Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	50	0	0	
Roof—Frame	0	40	0	0	
Roof—Covering	0	0	0	10	
Total	159	90	1125	35	
Steel structure (kg/m ²)					
Foundation—Strip footings	135	0	225	5	Industrial Airport buildings Seaport buildings
Foundation—Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	0	520	145	
Roof—Frame	0	0	0	145	
Roof—Covering	0	0	0	10	
Total	159	0	1645	325	
Transport					
	Concrete	Asphalt	Base material		
Roadways (kg/m)					
Major subdivision roadway	598	667	2453		
Minor subdivision roadway	0	552	2050		
Local street	0	552	2050		
Airport runways (kg/m ²)					
	305	234	427		
Seaports platforms (kg/m ²)					
	366	0	640		

3.2 | Stocks of transport

For transport-related stocks, we considered the share of paved roads in the road network, airports (buildings and runways), and main seaports (buildings and cargo platforms of larger seaports). During the transport stocks classification process, we consulted three GIS shapefile layers in parallel. The first shapefile was the same containing most of the building footprints of The Bahamas. From this, we filtered the ones corresponding to seaports and airports. The second shapefile layer is a November 2021 roads network file extracted from OSM through HOTOSM (Humanitarian OpenStreetMap Team, 2021b). The third OSM shapefile was a second November 2021 road network file extracted through Geofabrik GmbH (Geofabrik GmbH, 2021). The existing road network comprises two main types of roads: paved and unpaved. We further classified the paved roads into five main typologies based on the Design and Construction Guidelines for roads in The Bahamas: main road A, main road B, major subdivision, minor subdivision, and local street (Government of The Bahamas, 2004) (see S1).

The MIs for roads were obtained from the Design and Construction Guidelines for roads in The Bahamas, with specific designs for paved roads. The main materials for the paved carriageway were considered as asphalt of 4 cm thickness, with base layer of 20 cm thickness of base material, and concrete sidewalks (Government of The Bahamas, 2004, pp. 19, 21).

As the Building Code of The Bahamas is based generally on the South Florida (United States) Building Code (Ministry of Works & Utilities, 2003), we assumed that the Airport Pavement Design and Evaluation guidelines from the U.S. Department of Transportation were applicable for the MI of The Bahamas' airport runways. These guidelines contain information on the design and evaluation of pavements used by aircraft at civilian airports. The main materials for the runway pavement structure consist of a 10 cm thickness asphalt layer, a second 12 cm thickness concrete layer, and a 25 cm thickness base material layer (U.S. Department of Transportation, 2016, pp. 3–17).

The Building Code of The Bahamas does not contain distinct design specifications for seaports cargo platforms. As these would be under heavy loads like those in airport runways, we assumed that the Airport Pavement Design and Evaluation guidelines would also apply to the seaport's cargo platforms. The main materials for the platforms consisted of a 15 cm thickness concrete surface layer, and a 40 cm thickness base material layer (U.S. Department of Transportation, 2016, pp. 3–18). MIs in weight for roads, runways, and cargo platforms were estimated by calculating volumes of materials per unit of length or area, and multiplying them by the densities of concrete, hot-mix asphalt, and base materials. See MIs in Table 1.

Material stocks "MS" were calculated for each transport typology "t" and for each main material categories "m" by multiplying the transport type total GFA or total length "TX_(t)" by its corresponding "MI_(m)."

$$MS_{(t,m)} = TX_{(t)} \times MI_{(m)} \quad (4)$$

Total material stock "MS_{total}" per main material category and for transport type "TX_(t)" was calculated as follows:

$$\begin{aligned} MS_{total} = \sum MS_{(t,m)} = & MS_{Aggregate_{(t,m)}} + MS_{Timber_{(t,m)}} \\ & + MS_{Concrete_{(t,m)}} + MS_{Steel_{(t,m)}} + MS_{Asphalt_{(t,m)}} \\ & + MS_{Base_Material_{(t,m)}} \end{aligned} \quad (5)$$

To calculate total MS for each transport type, Equation (5) is applied for roads, airport buildings and runways, and seaport buildings and platforms (see results in Table 2).

3.3 | Near-future resource requirements using existing roads network as a proxy

We estimated potential near-future material requirements for buildings and roads grounded on two assumptions. First, we assume that areas that currently have low building density will grow in the future. Broadly, this can be approached by comparing high and low building and roads density areas. When looking at the evolution of building stocks, the presence of a road network is an early sign indication where development will likely happen. The second assumption corresponds to future roads' MS. We assume that currently unpaved roads will be upgraded to a paved roadway type in the future, thus changing their MIs and subsequently their MS (the reader is referred to S1 to consult the details on this methodology).

3.3.1 | Future buildings

As a first step, we examined the current density of both buildings and roads for the whole country. Areas that have a dense road network will likely have higher density of buildings around them, while the opposite will be true for more isolated roads. For different locations "i," we estimated the

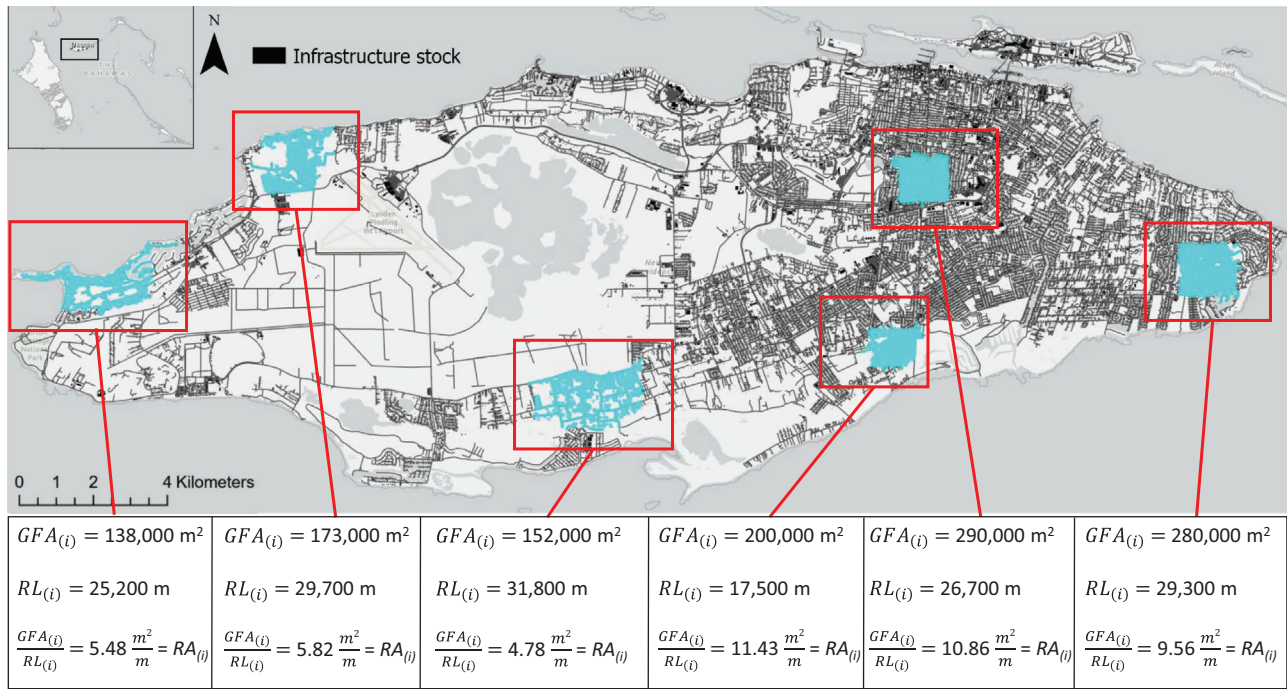


FIGURE 1 Ratios $RA_{(i)}$ of building gross floor area $GFA_{(i)}$ per road length $RL_{(i)}$ for different highlighted zones in New Providence in 2021. Source: Humanitarian OpenStreetMap Team (2021a, 2021b).

ratio “ $RA_{(i)}$ ” of building GFA “ $GFA_{(i)}$ ” versus road length “ $RL_{(i)}$ ” as follows:

$$RA_{(i)} = \frac{GFA_{(i)}}{RL_{(i)}} \quad (6)$$

A test-run was conducted for the capital island of New Providence (Figure 1). Specific zones present varying levels of development for both buildings and roads (i.e., east and west sides of the island), with $RA_{(i)}$ ranging from 9.6 to 11.4 for highly dense areas, and from 4.8 to 5.8 for less-dense areas.

To account for country-wide variations, we estimated total GFA and total RL for each district division by creating a homogeneous country-wide grid of $500 \text{ m} \times 500 \text{ m}$ and summarizing total GFA and RL per grid cell. We assumed that the potential maximum building development will be reached with a higher RA , thus, areas with a lower ratio will have the potential to reach a higher ratio in the future and hence, require more materials.

Total future building materials “FM” was calculated by accounting for the maximum potential ratio “ $RA_{(g)}$ ” of current GFA and current RL per each homogenized grid cell “g,” as well as accounting for current “ $GFA_{(d)}$ ” and “ $RL_{(d)}$ ” per district “d” and applying an average building MI.

$$FM_{(g,d)} = ((RA_{(g)} \times RL_{(d)}) - GFA_{(d)}) \times MI \quad (7)$$

Average MI was based on the overall MIs for each building typology and current shares of building MS typologies (see S1). Results (Table 3) are based on a conservative estimate of only 5% of total future building MS.

3.3.2 | Future roads

As a first step, we selected the roadways that will potentially become paved in the future. Within the OSM roads shapefile layer, we assumed that these include the roads with “path” and “unclassified” tags. We accommodated these under the “minor subdivision road/local street” typology. Additionally, through analyzing the roads network shapefile and directly observing satellite imagery (Google Earth Pro®, 2021), we included those areas containing “track” roads that display a distinct spatial arrangement characteristic of the preliminary works for future urban development (see S1). Future material requirements for each main component of the road were obtained by applying their respective MIs.

Future material stock “FMS” was calculated per each roadway type “ r ” and for each main material categories “ m ” by multiplying the roadway type total length “ $RL_{(r)}$ ” by its corresponding “ $MI_{(m)}$ ”.

$$FMS_{(r,m)} = RL_{(r)} \times MI_{(m)} \quad (8)$$

Total future material stock “ MS_{total} ” per main material category “ m ” and for a given roadway type “ $RL_{(r)}$ ” was calculated as follows:

$$FMS_{total} = \sum FMS_{(r,m)} = MS_{Concrete}_{(r,m)} + MS_{Asphalt}_{(r,m)} + MS_{Base_Material}_{(r,m)} \quad (9)$$

3.4 | Sea-level rise scenarios

Simulations were based on assessments of 1-m (intermediate–high projection) and 2-m (highest projection) estimates of global SLR by 2100 using the mean sea level in 1992 as the starting point, as presented by the National Oceanic and Atmospheric Administration (Parris et al., 2012). A third simulation of 3 m presents a more critical situation, where SLR continues to rise past the year 2100. The 1 arc-second global digital elevation model (DEM) data was obtained from the *U.S. Geological Survey* (USGS, 2022). We created polygon shapefile layers by filtering elevations from the DEM (see S1). The impacts of SLR were estimated by overlaying the SLR polygons on MS data and summarizing the MS that would be exposed under each scenario (see Figure 2 and Table 4).

Different patterns of development in the country were highlighted through directly observing historical satellite imagery (Google Earth Pro®, 2021) and reviewing land-use plans (Government of The Bahamas, 2010, 2017; IDB, 2018). Together with the generated SLR polygons, and the current spatial distribution of MS, we expanded on some potential effects of SLR over current stock and future development.

4 | RESULTS

4.1 | Current material stocks

Total MS was estimated at 75.9 million tonnes (Mt) or 191.2 tonnes per capita (t/cap) based on the 2021 population. Of this, total MS in buildings and transport represented 57% and 43% of the totals, with 43.1 Mt (108.6 t/cap), and 32.8 Mt (82.6 t/cap) respectively (see Table 2).

TABLE 2 Synthesis table showing the total existing material stocks (MS), by typology and main construction material in The Bahamas in 2021. Total MS: Units in Mt. Total MS per capita: units in t/cap. Note: Numbers may not add-up due to rounding. N.A., not applicable

Building typology	Aggregate	Timber	Concrete	Steel	Asphalt	Base material	Total MS	Total MS per capita
Residential	2.5	0.8	24.8	0.6	N.A.	N.A.	28.7	72.3
Commercial	1.0	0.2	10.0	0.2	N.A.	N.A.	11.5	29
Industrial	0.1	0.0	0.7	0.1	N.A.	N.A.	0.9	2.3
Government	0.1	0.0	1.2	0.0	N.A.	N.A.	1.4	3.5
Other	0.1	0.1	0.5	0.0	N.A.	N.A.	0.7	1.8
Building MS	3.7	1.2	37.2	1.0	N.A.	N.A.	43.1	108.6
Transport typology								
Paved road network	N.A.	N.A.	0.5	N.A.	3.3	12.4	16.2	40.8
Airport buildings	0.0	N.A.	0.5	0.1	N.A.	N.A.	0.6	1.5
Airport runways	N.A.	N.A.	4.2	N.A.	3.3	5.9	13.4	33.8
Seaport buildings	0.0	N.A.	0.3	0.1	N.A.	N.A.	0.4	1
Seaport platforms	N.A.	N.A.	0.8	N.A.	N.A.	1.5	2.3	5.8
Transport MS	0.1	N.A.	5.8	0.2	6.6	19.8	32.8	82.6
Total MS	3.8	1.2	43.0	1.2	6.6	19.8	75.9	191.2

Residential buildings account for 67% of total building MS, at 28.7 Mt (72.3 t/cap). Commercial typology accounts for around 27% of total building MS, at 11.5 Mt (29 t/cap). Government, industrial, and other uses represent around 3%, 2%, and 2% of building MS, respectively. Overall, concrete accounted for the largest share of total building MS at 86%, with aggregate (9%), timber (3%), and steel (2%) accounting for smaller shares.

The largest category of total transport MS was the paved road network (49% of total transport MS). The country has an extensive road network in most of its territory, with a length of around 11,300 km consisting of 5900 km of paved roads divided between major roads subdivision (approximately 820 km) and minor roads subdivisions (around 5080 km). Total paved road network MS was estimated at around 16.2 Mt (40.3 t/cap). Base material accounted for the greatest share of these MS at 76%, followed by asphalt (21%) and concrete (3%). Minor subdivision roadway/local street accounted for 80% of that total MS.

The second-largest category of total transport MS (43%) was airport buildings and runways. We identified more than 60 major, regional, and small airports amounting to a total MS of about 14 Mt (35.3 t/cap). The MS of runways was calculated at 13.4 Mt, of which the Lynden Pindling International Airport, the largest airport located in the capital city of Nassau, accounts for more than 30% of total airport MS. Buildings associated with airports were estimated at 0.6 Mt.

Seaports represent 8% of total transport MS. The country has about eight seaports of varying sizes, most of them being cruise ports, with a total MS of about 2.6 Mt (6.7 t/cap). The container yard platform of the Freeport Container Port, the largest port in the country, accounts for 50% of the total seaports MS. With a smaller share, seaport buildings were estimated at 0.4 Mt.

The concentration and distribution of building and transport stocks are spatially uneven. These are in very close proximity to the coastline, and MS hotspots are concentrated in a few districts like New Providence, the City of Freeport, and West Grand Bahama (see Table 3). Further, most MS and commercial activities are in urban centers, especially in the capital city of Nassau in New Providence.

4.2 | Building-to-road ratios and future material stocks

At the district level, Hope Town, the City of Freeport, Black Point, West Grand Bahama, and New Providence show relatively high building-to-road ratios, at 69, 64, 60, 57, and 50 m²/m, respectively, while some other districts like Spanish Wells and Ragged Island show values of almost 0 and 1 m²/m, respectively (see Table 3). West Grand Bahama and New Providence both have similar road lengths, but there is a great difference in their total building GFA (4 and 15 km², respectively). The Ragged Island and Spanish Wells districts each show total road lengths of around 10 km compared to the almost 2000 km of West Grand Bahama and New Providence, which indicates the high variation in in-use stock and distribution among the country's districts.

Total future MS was estimated at 36 Mt. Of this, future building MS corresponded to roughly 31.5 Mt. For future roads, results show that additions to stocks amount to around 4.5 Mt of new material and 2000 km of upgraded paved roads. Future stocks might be mostly distributed in the districts of West Grand Bahama, New Providence, Central Abaco, and Exuma (see Table 3), which are currently some of the main urban centers in the country. To the authors' knowledge, only few land-use zoning or planning for many of the major islands and family islands has been developed. Nonetheless, our results have managed to produce similar results on future development zoning (see Supporting Information S3, SD_Figure 13) as the ones proposed under the Andros Master Plan and Sustainable Nassau Plan (Government of The Bahamas, 2017, pp. 15–17; IDB, 2018, pp. 42, 43).

4.3 | Effects of sea-level rise scenarios

Results show that a total of 3.5 Mt (4.5%), 5.9 Mt (7.8%), and 8.9 Mt (11.7%) of total building and transport stock would be exposed under the 1-, 2-, and 3-m SLR scenarios, respectively. Overall, transport stocks would be the most affected under any scenario, both in volume and in percentages. Moreover, airport and seaport stocks are demonstrated to have significant exposure under the simulations (~12% and ~39% exposure, respectively, under 1-m SLR scenario), while road stocks show the least transport exposure (see Figure 2 and Table 4).

Among buildings, residential and commercial MS show greater exposure in all scenarios, with results varying from 0.2 to 0.8 Mt. For roads, minor subdivision roadways/local streets are most exposed, amounting up to 1 Mt. Buildings associated with both airports and seaports show significantly less exposure than runways and cargo platforms.

Most of the exposed MS is in the northern section of the country, specifically in Grand Bahama and Abaco islands. The central and southern sections of the country show relatively lower levels of exposure, which is also reflected in the higher elevation terrains and lower levels of infrastructure development.

TABLE 3 Estimations of current (year 2021) and future building material stocks for each district in The Bahamas. $GFA_{(d)}$, gross floor area per district “d,” $RL_{(d)}$, road length per district “d,” $RA_{(g)}$, max ratio of GFA/RL per grid cell “g.” Note: Numbers may not add-up due to rounding

District name	Current building MS (Mt)	$RA_{(g)}$ (m^2/m)	$RL_{(d)}$ (km)	$GFA_{(d)}$ (km^2)	5% of total future building MS (Mt)	Current roads MS (Mt)	Upgraded roads length (km)	Future roads MS (Mt)	Total future MS buildings + roads (Mt)
Acklins	0.10	14.99	171	0.07	0.22	0.17	54.1	0.12	0.34
Berry Islands	0.22	29.25	93	0.13	0.23	0.04	56.8	0.13	0.36
Biminis	0.22	16.65	55	0.13	0.07	0.08	10.9	0.02	0.09
Black Point	0.07	59.69	58	0.04	0.30	0.10	7	0.02	0.32
Cat Island	0.35	21.53	323	0.21	0.60	0.47	88.4	0.20	0.80
Central Abaco	1.68	33.42	880	1.03	2.51	0.90	87.6	0.20	2.71
Central Andros	0.07	5.52	60	0.04	0.03	0.12	5.7	0.01	0.04
Central Eleuthera	0.47	8.65	160	0.29	0.10	0.35	25.4	0.06	0.15
City of Freeport	2.37	63.80	289	1.40	1.51	0.58	15.77	0.03	1.54
Crooked Island	0.08	6.93	82	0.06	0.05	0.11	24.51	0.06	0.10
East Grand Bahama	0.30	10.63	408	0.17	0.37	0.26	190.5	0.43	0.80
Exuma	0.64	42.80	598	0.38	2.23	1.09	73.42	0.17	2.40
Grand Cay	0.04	12.66	6	0.03	0.00	0.01	3.94	0.01	0.01
Harbour Island	0.34	10.35	35	0.20	0.01	0.09	0.28	0.00	0.01
Hope Town	0.92	68.61	149	0.57	0.86	0.26	32.54	0.07	0.93
Inagua	0.17	6.03	486	0.13	0.25	0.07	67.9	0.15	0.40
Long Island	0.49	22.90	542	0.31	1.07	0.65	50.27	0.11	1.19
Mangrove Cay	0.05	7.82	40	0.03	0.02	0.03	15.33	0.03	0.06
Mayaguana	0.05	2.10	246	0.04	0.04	0.03	46.54	0.11	0.15
Moore's Island	0.08	17.70	10	0.05	0.01	0.01	6.66	0.02	0.03
New Providence	24.68	49.99	1,959	14.60	7.38	4.81	36.29	0.08	7.46
North Abaco	0.29	9.94	240	0.19	0.19	0.29	26.65	0.06	0.26
North Andros	0.87	18.56	846	0.53	1.34	0.84	131.8	0.30	1.64

(Continues)

TABLE 3 (Continued)

District name	Current building MS (Mt)	RA _(g) (m ² /m)	RL _(d) (km)	GFA _(d) (km ²)	5% of total future building MS (Mt)	Current roads MS (Mt)	Upgraded roads length (km)	Future roads MS (Mt)	Total future MS buildings + roads (Mt)
North Eleuthera	0.97	32.22	370	0.60	1.00	0.82	37.09	0.07	1.07
Ragged Island	0.00	0.20	9	0.00	0.00	0.02	0	0.00	0.00
Rum Cay	0.02	6.40	78	0.02	0.04	0.02	15.34	0.03	0.08
San Salvador	0.23	7.19	205	0.14	0.12	0.37	18.26	0.04	0.16
South Abaco	0.16	10.89	625	0.10	0.59	0.36	33.43	0.08	0.67
South Andros	0.24	23.07	89	0.15	0.17	0.15	21.23	0.05	0.22
South Eleuthera	0.58	38.88	390	0.36	1.31	0.55	57.69	0.10	1.41
Spanish Wells	0.00	0.96	13	0.00	0.00	0.02	1.6	0.00	0.00
West Grand Bahama	6.22	56.75	1,823	3.70	8.84	2.56	769.2	1.74	10.57
Totals	43.1		11,338	25.7	31.5	16.2	2,012.1	4.5	36

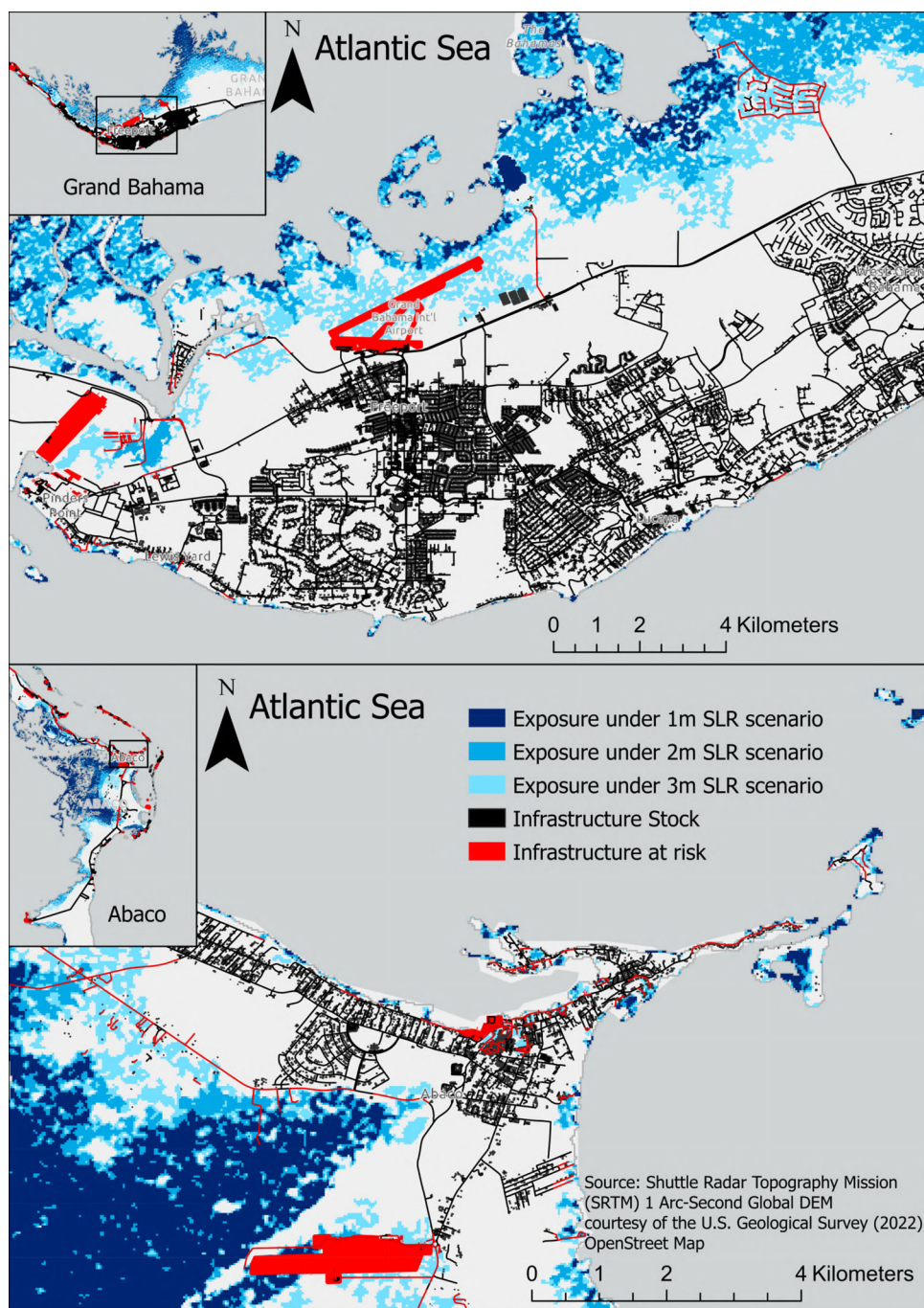


FIGURE 2 Potential material stocks at risk from sea-level rise in The Bahamas. The image shows Grand Bahama and the Abaco islands. Sources: own simulations based on data from Humanitarian OpenStreetMap Team (2021a, 2021b) and USGS (2022).

TABLE 4 Total existing material stocks (MS) and exposure (absolute value and percentage) for each MS typology under the different sea-level rise (SLR) scenarios in The Bahamas. These were based on estimates of global SLR by 2100 (Parris et al., 2012); 1 m: intermediate-high projection; 2 m: highest projection; 3 m: extra simulation presenting a more critical situation where SLR continues to rise past the year 2100

SLR scenario		1 m		2 m		3 m	
Material stock typology	Total MS (Mt)	MS exposed (Mt)	Typology (%)	MS exposed (Mt)	Typology (%)	MS exposed (Mt)	Typology (%)
Building							
Residential	28.7	0.2	0.7	0.4	1.4	0.8	2.7
Commercial	11.5	0.2	1.5	0.2	2.2	0.4	3.8
Industrial	0.9	0.0	1.8	0.0	3.3	0.1	16.2
Government	1.4	0.0	0.0	0.0	0.1	0.0	0.6
Other	0.7	0.0	1.1	0.0	2.2	0.4	56.0
TOTAL	43.1	0.4	0.9	0.7	1.6	1.8	4.1
Road							
Major subdivision/roadway	3.2	0.1	3.1	0.2	7.0	0.5	14.3
Minor subdivision/local street	13.0	0.3	2.1	0.5	3.9	1.0	7.5
TOTAL	16.2	0.4	2.3	0.7	4.5	1.4	8.8
Airport							
Airport buildings	0.6	0.0	1.7	0.0	3.3	0.1	8.3
Airport runways	13.4	1.6	12.0	2.5	18.7	3.7	27.4
TOTAL	14.0	1.6	11.6	2.5	18.0	3.7	26.6
Seaport							
Seaport buildings	0.4	0.0	0.3	0.0	0.5	0.0	1.1
Seaport platforms	2.3	1.1	45.7	1.9	83.9	2.0	86.5
TOTAL	2.7	1.1	38.9	1.9	71.6	2.0	73.9
TOTAL MS	75.9	3.5	4.5	5.9	7.8	8.9	11.7

5 | DISCUSSION

5.1 | Open-source data and MSA

This study did not rely on the collection of first-hand fieldwork measurements of MS characteristics, nor on official country spatial databases. OSM was utilized as an alternative source of those official spatial databases, functioning as primary data for the analysis.

From our working OSM files, we observed that few building footprints were missing from small zones, while the road network was virtually complete in the whole country. Following our approach, one would be unable to generate consistent MS estimates for places that do not have any existing building footprints and/or road segments recorded in OSM files yet. Notwithstanding these limitations, our methodology managed to reach similar estimates of MS when cross-checked with independent studies from across the world with more “traditional” or “official” data sources (see Figure 3). The utilization of our methodology and OSM data, thus, could be comparable to more established MS accounting methodologies.

The potentials advantages of OSM as main data source for MS assessments are profound. Similar to The Bahamas, spatially explicit data on MS are not available in many other countries, especially SIDS and developing countries of the Global South. OSM enables a much-needed estimation of such countries' MS with relatively low time and resource investment. It aids in mapping urban forms and MS development, and informs about potential vulnerabilities and risks. Furthermore, OSM data is relatively rapidly updated by the crowdsourcing community, potentially enabling historical MS coverage analyses.

Nevertheless, care must be taken to ensure OSM data quality and completeness to reduce uncertainties. In our study, historical OSM data were incomplete and thus prohibited a time-series assessment. Contributing to open-access crowdsourced data calls for sufficient general resources (e.g., internet, geospatial skills), extra scrutiny, highlighting the need for responsible use and clear reporting of results and uncertainties, and their potential implications. For The Bahamas, the lack of other data sources limits the assessment of these uncertainties and their implications beyond a simple qualitative assessment.

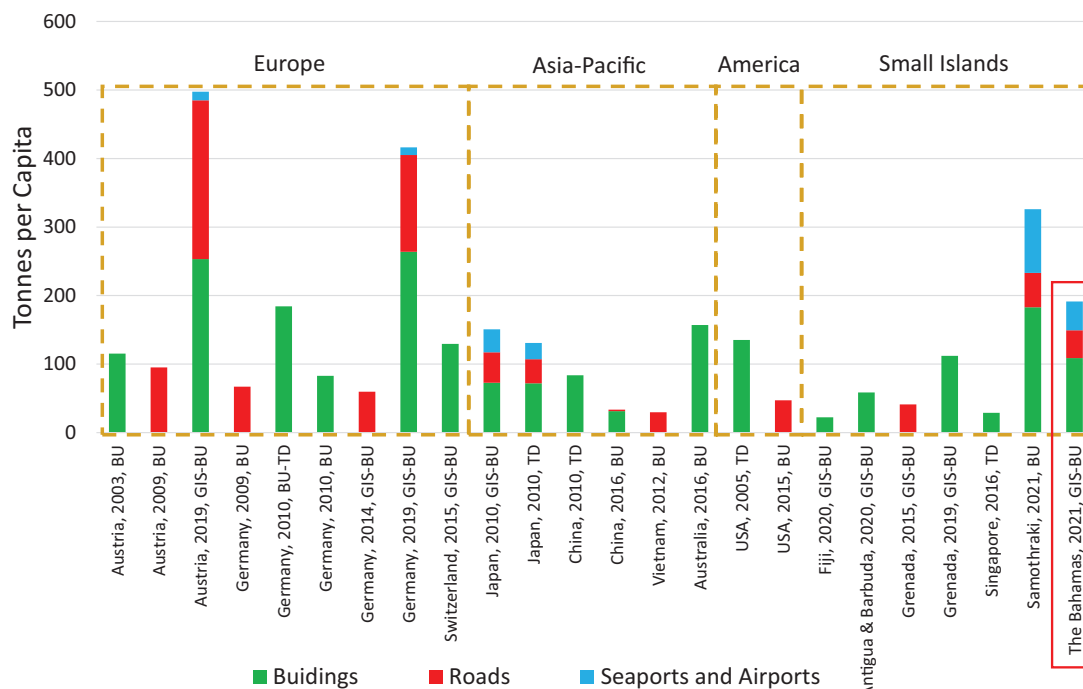


FIGURE 3 Material stock for different territories. Horizontal axis presents Case study–Year analyzed–Estimation approach. Source: Austria (Daxbeck et al., 2009; Haberl et al., 2021; Wiedenhofer et al., 2015); Germany (Knappe et al., 2015; Ortlepp et al., 2016; Schiller et al., 2017; Wiedenhofer et al., 2015); Switzerland (Heeren & Hellweg, 2019); Japan, (Hashimoto et al., 2007; Tanikawa et al., 2015); China (Huang et al., 2013; Zhang et al., 2019); Vietnam (Nguyen et al., 2019); Australia (Soonsawad et al., 2022); USA (Miatto et al., 2017; Wiedenhofer et al., 2015); Fiji (Merschroth et al., 2020); Antigua and Barbuda, (Bradshaw et al., 2020); Grenada (Symmes et al., 2019; Ye, 2022); Samothraki (Noll et al., 2021); Singapore (Arora et al., 2019); The Bahamas (Current study). Abbreviations correspond to estimation approaches: BU, bottom-up; GIS-BU, GIS-based bottom-up; TD, top-down. The underlying data for this figure can be found in Supporting Information S5.

5.2 | The Bahamas' material stocks and sustainability

In The Bahamas, the relatively high levels of transport MS may translate into better connectivity and more efficient means to mobilize people and resources within the country and from/to external economies. However, this comes with a multitude of environmental issues like air/water/soil pollution. In addition to being a contributor to climate change, transport MS is highly impacted by it (i.e., more floods due to SLR). For residential and commercial buildings MS, our results reflect the importance that tourism has in the economy. There is an impending need to allocate resources to service this industry in the form of MS. Nonetheless, the benefits produced by this sector (i.e., revenue, job generation) oftentimes compete with the costs of tourism activities (i.e., a decline of coastal protection, environmental degradation).

Besides the initial resource investment for their use in construction, MS require extra resources for expansion, maintenance, or operation. The Bahamas is especially dependent on foreign economies for the supply of these construction materials, like metals and cement. The Bahamian economy exhibits extractive resource patterns that are focused on only few natural resources, including sand and gravel, which accumulate as stocks. The quantity of materials removed from the stocks after their service lifetime is also considerable, while these outflows usually remain unrecovered (Martin del Campo et al., 2023). Stabilizing the infrastructure stock and expanding its service lifetime are some means to reduce material use and outflows. Additionally, MS may serve as a latent opportunity to bring materials at their end-of-life back to the economy through urban mining, thus reducing waste and preventing further exploitation of virgin resources. Through this study, the extent of recovery and reuse of materials is highlighted by the elevated shares of concrete and base materials in MS. However, the country's ability to harness and implement strategies of recovery and reuse of these latent materials are further jeopardized by climate change vulnerability and extreme events that severely damage these stocks (Bello, Hendrickson et al., 2020; ECLAC, 2020). With a low resource-base, the issue of import dependency over non-replaceable construction materials may be aggravated by price volatility and disruptions in global supply chains, as seen with the conflict in Ukraine (IMF, 2022).

Notwithstanding the key role that resilient and functioning MS plays in achieving sustainable development, there are still complex trade-offs and synergies between MS and sustainability requiring further assessment. A built environment that provides high-quality services with lower resource needs, for longer periods, and which efficiently closes material cycles, could be a potential solution in the development agenda. Strategies should encompass a holistic long-term sustainability vision, adapted to the case study, with efficient and resilient infrastructure development planning and climate change adaptation strategies.

TABLE 5 Potential current and future risks associated with the state of The Bahamas as seen in our analysis

Status of the country	Current risks	Future risks
High levels of development concentrated in a few urban centers	Damages to existing ecologically sensitive areas. This may translate into overall ecosystem health degradation	Additional development may threaten the balance of the natural system, further impacting hydrological cycles and causing loss of habitat for species, among others
	Relatively large volumes of waste generation	Health issues and environmental pollution
Material stocks close to the coastline	Potential stock damage/loss to extreme events, such as flooding or hurricanes	Further material stocks damage/loss to SLR
	Interruption of critical services that the country depends on, such as basic needs provisioning, tourism activities, etc.	Reconstruction/relocation of assets impacted by SLR due to loss of land
	Competition with other land uses as development is pushed to inland zones	SLR of 1-, 2-, and 3-m could mean the disappearance of 6%, 12%, and 22% of the total national territory, respectively
		Coastal squeeze likely to occur, pushing development into already scarce higher elevation grounds
Underdeveloped areas across the country		Displacement of population
		Salt water intrusion due to SLR could reduce the already limited resource base and cause health issues due to salt water intrusion in poorly built waste disposal facilities
	Untapped potential for job creation, for exploitation of resources, and for revenue income generation from economic activities such as tourism, give rise to increased poverty, dependency on external aid, social inequality, and health risks, especially in some of the Family Islands	Development calls for more resources for expansion (usually imported), which could lead to overuse of resources, increased waste generation that often remains within the limits of the island, among others, and that could negatively impact over social, economic, and environmental systems
	Limited infrastructure opportunities and/or poorly constructed facilities affect the population's livelihood and heighten the risks of displaying undereducation, malnutrition, and health issues, among others	Population and infrastructure at risk if unregulated development occurs in hazard-prone/ecologically sensitive areas

5.3 | Current and future risks in The Bahamas

Material stocks and development in a country are linked directly to an improved standard of life and advance sustainability; however, specific configurations and combinations of resource flows and stocks contribute to the system's exposure to risk. Singh et al. (2022, p. 2) define socio-metabolic risks (SMR) as the "systemic risk associated with the availability of critical resources, the integrity of material circulation, and the (in)equitable distribution of derived products and societal services in a socio-ecological system." In The Bahamas, we noticed high MS density in specific urban centers, with uneven distribution across the country, oftentimes concentrated close to the coastline. The availability, integrity, and circulation of critical resource flows are largely reliant on a combination of key MS. Moreover, disturbances like climate change and SLR pose major threats to existing and future MS, contributing to the proliferation of SMR (see Table 5).

Transport infrastructure in The Bahamas is one of the highest among the Caribbean SIDS (see Supporting Information S4). This can be partially attributed to the country's archipelagic nature and its vast territory. As The Bahamas has a limited resource base and imports up to 80%–90% of its basic requirements (Bradshaw et al., 2020; Dorodnykh, 2017; FAO, 2021; NREL, 2015; Symmes et al., 2019; Yu, 2017), a disruption in the operation of any of the transport infrastructure (i.e., due to climate change and SLR) would have widespread repercussions. Strengthening structural, financial, and social resilience is key to reducing risks and vulnerabilities in the system and to hasten recovery responses in case of disasters.

Nonetheless, risks should not be only understood through the impacts of SLR on MS.

- First, as The Bahamas is a low-lying country with relatively small islands, SLR makes it particularly vulnerable to land loss and impacts to MS. This could further impact over the already limited territory and scarce arable land, potentially causing saltwater intrusion in surface and ground water, compromising the quality of water supply and food security for local people. Moreover, development is already being pushed to very

limited inland areas with higher elevation, prioritizing zones where future squeeze will likely occur, as in Grand Bahama and Abaco islands (see timelapse satellite imagery from Google Earth Pro® (2021)).

- Second, current development of urban centers is reaching its expansion limits, like in New Providence, giving rise to complex challenges in transport, housing, waste management, and other social services, which carry their own set of risks (i.e., environmental pollution, and ecosystem degradation). Along with environmental issues, complex logistics in dense urban centers make it difficult to mobilize people and resources in a timely and efficient manner. Housing must account for accommodation for tourist arrivals, competing with local residents for land space. Waste flow generation could translate into overall ecosystem degradation, impacts on water quality and water security, and health issues.
- Third, the full potential of The Bahamas remains untapped. For many islands in the country, there is a lack of essential infrastructure to support its people and its environment and harness the island's wealth of natural assets, thus missing many opportunities for job creation, for exploitation of resources, and for revenue income generation from economic activities like tourism. For the less populated islands, the lack in infrastructure limits the development potential of the island and its inhabitants. Action is needed to assess potential socioeconomic impacts of a future expansion, to manage the rate of accumulation of materials, territorial ordering, and future material output.

Overall, the direct impacts on transport infrastructure are profound, particularly for SIDS. These often spend large part of their public budget on transport infrastructure, either on regular maintenance or repairs from shocks (The World Bank, 2017). Transport disruptions are one of the main obstacles to recovery when extreme events occur (United Nations, 2021). The cascading effects arising from supply chain disruptions and critical infrastructure damage can spread through other components like other production or demand centers (i.e., power networks), thus further increasing the vulnerability of the system (Renn et al., 2020; Verschuur et al., 2022).

6 | CONCLUSION

This study comprehensively examined both buildings and transport stocks for a small island nation as part of the MSA methodology based on freely available data. We estimated current and future MS by combining available GIS data from OSM and data with stocks MIs, and examined current and future MS patterns that influence the system's exposure to risks. It offers both qualitative and quantitative insights into how stocks are spatially distributed and built-up, and gives observations on how the built environment evolves and is impacted by SLR.

Material stocks, particularly transport, are at risk from climate change. A large share of MS of airports (~12%), seaports, harbors, marinas, and ferry terminals (~39%) in The Bahamas are at risk of future flooding, which will likely cause disruptions in supply chain operations, including stocks damage across the country. More efforts to better understand the composition and dynamics of MS and environmental threats is essential for current and future sustainable development, especially in a SIDS context.

While the Planning and Subdivision Bill (2010) of The Bahamas establishes that there shall be a land-use plan and territorial ordering for each island consistent with all national land-use development policies, substantial delays remain as only few have been prepared (e.g., Andros Master Plan, or Sustainable Nassau Plan) (Government of The Bahamas, 2017; IDB, 2018). Flexible and robust policy frameworks should be implemented to hasten long-term development planning and adaptation strategies that address the trade-offs of future infrastructure development in ecologically sensitive areas. Land and sea pressures over these areas can impact on natural ecosystems, reducing their capacity to provide essential services. This would have a doubly negative effect through the loss of tourism resource base and a decline in coastal protection, further increasing threats by SLR and storm surges.

The infrastructure of the country urgently needs to be improved with a resilient and sustainable approach in mind. Future work in stock management must consider disaster risks. A combination of protection, accommodation, and managed retreat are potential strategies to manage these. Identifying and mapping strategic areas for critical buildings, transport nodes, and networks to determine potential vulnerabilities and risks in the system are also critical. Future work should include an analysis of the most vulnerable ecological areas in the case of a possible coastal squeeze.

Potential development strategies may include the combined use of natural, vegetated, hard, and engineered coastal defense structures that can reduce the need for additional MS and lower overall infrastructure expenditure (Silver et al., 2019; van Zelst et al., 2021). Coastal ecosystems conservation is a financially beneficial option vis-à-vis for the restoration of these ecosystems. However, if this restoration is required or desired, a comprehensive spatial analysis of restoration opportunities will be helpful for the identification of the most cost-efficient restoration sites with the greatest benefit for coastal protection against SLR and storm surge impacts (Lester et al., 2020).

The precision of this analysis is dependent on data quality and completeness. Our study gives a general overview of the potential that experimenting with open-source data may offer in advancing MS studies and to what extent OSM is helpful for MS estimations. As OSM and DEM data is freely available, our methodology could be relatively easy to replicate for other case studies; however, the particularities of data collection for each case could be a challenge. Uncertainty could be reduced by combining different data sources (i.e., satellite imagery with OSM data and official statistics, primary data collection), giving a more robust representation of what is physically available on the ground. The DEM utilized for SLR simulations highlighted flood-susceptible areas that may benefit from further analysis based on higher resolution data. Further improvements on our

methodology mainly concern the accurate identification of infrastructure elements by typology, the addition of unrecorded building footprints and road network segments, more detailed MI data, and the utilization of finer DEM resolutions.

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SUPPORTING INFORMATION

The supporting information provides details on the methodological approach (S1) taken in the main manuscript to quantify current and future material stocks in The Bahamas for the year 2021, as well as more insight to account for the impacts of sea-level rise on material stocks across the country. Moreover, it provides a small tutorial on how to work with historical OpenStreetMap (OSM) data files (S2) as a way to aid in the process of spatial analysis of historical data for a specific zone in the world. Additionally, we provide two supporting information files with supplementary data on figures (S3) and tables (S4) for the main text and also for the supplementary information files (S2). Supporting Information file (S5) provides underlying data in tabular form for Figure 3 in the main text.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available under the OpenStreetMap (OSM) platform at <https://planet.openstreetmap.org/planet/>. A brief tutorial on how to download and operate historical OSM files is presented under the Supporting Information (SI) files. Most recent OSM data extracts can be found under the Humanitarian OpenStreetMap Team (HOTOSM) platform at <https://data.humdata.org/dataset>, as well as under the Geofabrik GmbH platform at <https://download.geofabrik.de>. All other data supporting the findings of this study are available within the article and its Supporting Information files or are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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