The Bahamas at risk: material stocks, sea-level rise, and the implications for development

Martin del Campo, F.; Singh, S.J.; Fishman, T.; Thomas, A.; Drescher, M.

DOI: 10.1111/jiec.13402

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH ARTICLE

The Bahamas at risk

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

Francisco Martin del Campo[1] | Simron Jit Singh[1] | Tomer Fishman[2] | Adelle Thomas[3] | Michael Drescher[4]

[1]School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, Canada

[2]Institute of Environmental Sciences (CML), Leiden University, Leiden, Netherlands

[3]Climate Change Adaptation and Resilience Research Centre, University of The Bahamas, Nassau, The Bahamas

[4]School of Planning, University of Waterloo, Waterloo, Ontario, Canada

Correspondence
Francisco Martin del Campo, School of Environment, Enterprise and Development, University of Waterloo, 200 University Avenue West N2L 3G1, Waterloo, Ontario, Canada.
Email: fxfelixm@uwaterloo.ca

Editor Managing Review: Lynette Cheah

Funding information
Mexican National Council for Science and Technology (CONACyT), Energy Council of Canada (ECC), Waterloo Institute for Sustainable Energy (WISE), School of Environment, Enterprise and Development (SEED) from the University of Waterloo

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 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; Kloostra, 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 km^2 (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/m^2) for these main typologies. GFA (in m^2) for each individual building "*b*" was calculated through estimating the individual building footprint area$_{(b)}$ and multiplying it with its corresponding number of stories$_{(b)}$.

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

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$_{(m)}$."

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

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$_{\text{total}}$" per main material category and for a building "GFA$_{(b)}$" was calculated as follows:

$$\text{MS}_{\text{total}} = \sum \text{MS}_{(b,m)} = \text{MS\_Aggregate}_{(b,m)} + \text{MS\_Timber}_{(b,m)} + \text{MS\_Concrete}_{(b,m)} + \text{MS\_Steel}_{(b,m)} \tag{3}$$

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	
Foundation—Ground slab	24	0	450	10	
Floors	0	0	450	10	Residential (85%)
Walls	0	0	520	1	Commercial
Roof—Frame	0	40	0	0	Government
Roof—Covering	0	0	0	10	
Total	159	40	1645	36	
Timber structure (kg/m^2)					
Foundation—Pad footings	45	0	45	1	
Foundation—Posts	0	0	300	5	Residential (10%)
Floors	0	0	0	20	Other
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	
Foundation—Ground slab	24	0	450	10	
Floors	0	0	450	10	Residential (5%)
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	
Foundation—Ground slab	24	0	450	10	
Floors	0	0	450	10	Industrial
Walls	0	0	520	145	Airport buildings
Roof—Frame	0	0	0	145	Seaport buildings
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 "$MI_{(m)}$."

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

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

$$\begin{aligned} MS_{total} = \sum MS_{(t,m)} &= MS\_Aggregate_{(t,m)} + MS\_Timber_{(t,m)} \\ &+ MS\_Concrete_{(t,m)} + MS\_Steel_{(t,m)} + MS\_Asphalt_{(t,m)} \\ &+ MS\_Base\_Material_{(t,m)} \end{aligned} \tag{5}$$

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

$GFA_{(i)} = 138{,}000$ m^2	$GFA_{(i)} = 173{,}000$ m^2	$GFA_{(i)} = 152{,}000$ m^2	$GFA_{(i)} = 200{,}000$ m^2	$GFA_{(i)} = 290{,}000$ m^2	$GFA_{(i)} = 280{,}000$ m^2
$RL_{(i)} = 25{,}200$ m	$RL_{(i)} = 29{,}700$ m	$RL_{(i)} = 31{,}800$ m	$RL_{(i)} = 17{,}500$ m	$RL_{(i)} = 26{,}700$ m	$RL_{(i)} = 29{,}300$ m
$\frac{GFA_{(i)}}{RL_{(i)}} = 5.48\,\frac{m^2}{m} = RA_{(i)}$	$\frac{GFA_{(i)}}{RL_{(i)}} = 5.82\,\frac{m^2}{m} = RA_{(i)}$	$\frac{GFA_{(i)}}{RL_{(i)}} = 4.78\,\frac{m^2}{m} = RA_{(i)}$	$\frac{GFA_{(i)}}{RL_{(i)}} = 11.43\,\frac{m^2}{m} = RA_{(i)}$	$\frac{GFA_{(i)}}{RL_{(i)}} = 10.86\,\frac{m^2}{m} = RA_{(i)}$	$\frac{GFA_{(i)}}{RL_{(i)}} = 9.56\,\frac{m^2}{m} = RA_{(i)}$

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:

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

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 m × 500 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.

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

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 "$MI_{(m)}$."

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

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

$$FMS_{total} = \sum FMS_{(r,m)} = MS\_Concrete_{(r,m)} + MS\_Asphalt_{(r,m)} + MS\_Base\_Material_{(r,m)} \tag{9}$$

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 m^2/m, respectively, while some other districts like Spanish Wells and Ragged Island show values of almost 0 and 1 m^2/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 km^2, 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**

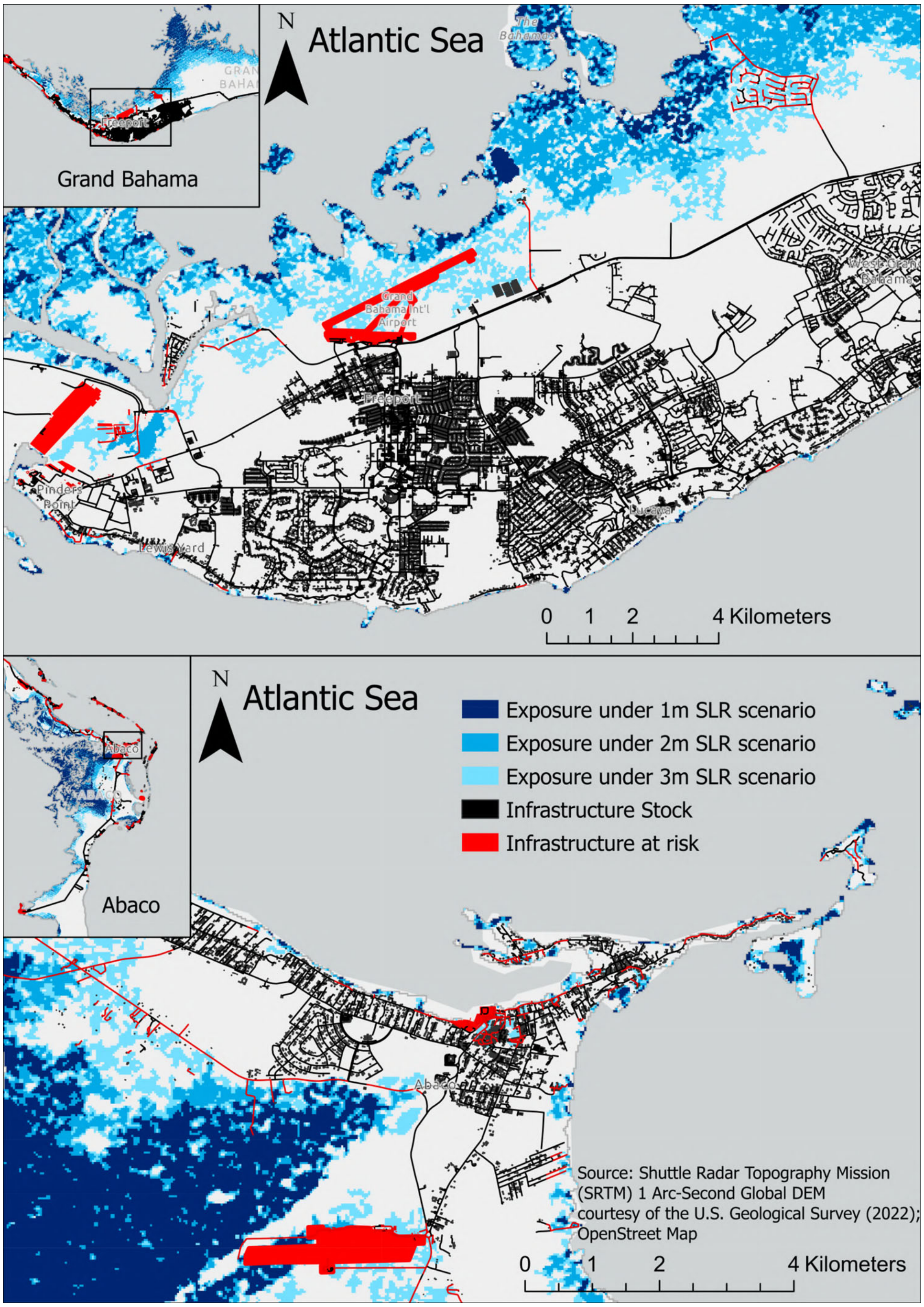

FIGURE 2 Potential material stocks at risk from sea-level rise in The Bahamas. The image shows Grand Bahama and the Abaco islands. *Sources*: own simulations based on data from Humanitarian OpenStreetMap Team (2021a, 2021b) and USGS (2022).

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 subdivisionroadway	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.

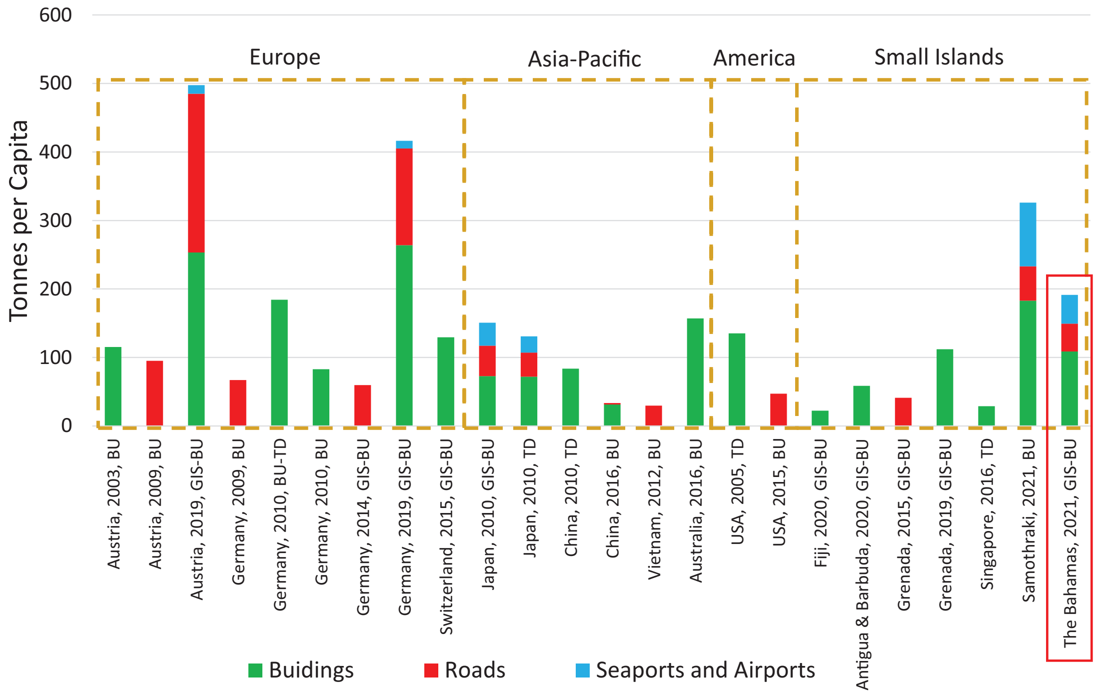

FIGURE 3 Material stock for different territories. Horizontal axis presents Case study–Year analyzed–Estimation approach. *Source*: Austria (Daxbeck et al., 2009; Haberl et al., 2021; Wiedenhofer et al., 2015); Germany (Knappe et al., 2015; Ortlepp et al., 2016; Schiller et al., 2017; Wiedenhofer et 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
		SLR of 1-, 2-, and 3-m could mean the disappearance of 6%, 12%, and 22% of the total national territory, respectively
	Competition with other land uses as development is pushed to inland zones	Coastal squeeze likely to occur, pushing development into already scarce higher elevation grounds
		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
Underdeveloped areas across the country	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.

ACKNOWLEDGMENTS

This project was funded by the Mexican National Council for Science and Technology (CONACyT), the Energy Council of Canada (ECC), the Waterloo Institute for Sustainable Energy (WISE), and the School of Environment, Enterprise and Development (SEED) from the University of Waterloo. The authors thank Dr. Maud Lanau (University of Sheffield) for sharing interesting data on material stocks, which helped them in their research purposes.

Open access funding enabled and organized by Projekt DEAL.

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.

ORCID

Francisco Martin del Campo https://orcid.org/0000-0001-5963-7290
Simron Jit Singh https://orcid.org/0000-0001-7012-893X
Tomer Fishman https://orcid.org/0000-0003-4405-2382
Adelle Thomas https://orcid.org/0000-0002-0407-2891

REFERENCES

Alam, M. (2015). *Application of national census data for vulnerability assessment and spatial planning in Grenada* [Thesis, University of Twente]. https://essay.utwente.nl/83968/1/alam.pdf

Aleksandrova, M., Balasko, S., Kaltenform, M., Malerba, D., Mucke, P., Neuschäfer, O., Radtke, K., Prütz, R., Strupat, C., Weller, D., & Wiebe, N. (2021). *WorldRiskReport 2021*. Bündnis Entwicklung Hilft, Ruhr University Bochum – Institute for International Law of Peace and Armed Conflict (IFHV). https://reliefweb.int/attachments/8629d457-6584-3f5f-93d2-beeb20aae083/2021-world-risk-report.pdf

Alleyne, D., Hendrickson, M., McLean, S., Pantin, M., & Skerrette, N., *Economic survey of the Caribbean 2021* (p. 30) (106 (LC/TS.2021/222-LC/CAR/TS.2021/8). Studies and perspectives series-ECLAC Subregional Headquarters for the Caribbean. https://repositorio.cepal.org/bitstream/handle/11362/47743/3/S2101019_en.pdf

Arora, M., Raspall, F., Cheah, L., & Silva, A. (2019). Residential building material stocks and component-level circularity: The case of Singapore. *Journal of Cleaner Production*, *216*, 239–248. https://doi.org/10.1016/j.jclepro.2019.01.199

Bello, O., Hendrickson, M., Marcano, B., Pantin, M., Mery, G., Espiga, C., Espiga, F., González, M., Flores, A., Ibarra, F., Marconi, S., Williams, R., Attademo-Hirt, F., Nelson, M., & Zane, Z. (2020). *Assessment of the effects and impacts caused by Hurricane Irma*. The Bahamas 2017. Inter-American Development Bank. https://doi.org/10.18235/0002617

Bradshaw, J., Singh, S. J., Tan, S.-Y., Fishman, T., & Pott, K. (2020). GIS-based material stock analysis (MSA) of climate vulnerabilities to the tourism industry in Antigua and Barbuda. *Sustainability*, *12*(19), 8090. https://doi.org/10.3390/su12198090

Deopersad, C., Persaud, C., Chakalall, Y., Bello, O., Masson, M., Perroni, A., Carrera-Marquis, D., Fontes de Meira, L., González, C., Peralta, L., Skerette, N., Marcano, B., Patin, M., Vivas, G., Espiga, C., Allen, E., Ruiz, E., Ibarra, F., Espiga, F., … Nelson, M. (2020). *Assessment of the effects and impacts of Hurricane Dorian in The Bahamas* (2020th ed.). Inter-American Development Bank. https://doi.org/10.18235/0002582

CRED, & UNISDR. (2018). *Economic losses, poverty & disasters: 1998–2017*. United Nations Office for Disaster Risk Reduction (UNISDR) and the Centre for Research on the Epidemiology of Disasters (CRED). https://www.preventionweb.net/files/61119_credeconomiclosses.pdf

Daxbeck, H., Buschmann, H., Neumayer, S., & Brandt, B. (2009). *Methodology for mapping of physical stocks*. Resource Management Agency (RMA). http://forwast.brgm.fr/Documents/Deliverables/Forwast_D23.pdf

Deetman, S., de Boer, H. S., Van Engelenburg, M., van der Voet, E., & van Vuuren, D. P. (2021). Projected material requirements for the global electricity infrastructure – Generation, transmission and storage. *Resources, Conservation and Recycling*, *164*, 105200. https://doi.org/10.1016/j.resconrec.2020.105200

Dorodnykh, E. (2017). *Economic and social impacts of food self-reliance in the Caribbean* (1st ed.). Springer International Publishing: Imprint: Palgrave Macmillan. https://doi.org/10.1007/978-3-319-50188-8

ECLAC. (2020). *Assessment of the effects and impacts of the Hurricane Matthew: The Bahamas.* Economic Commission for Latin America and the Caribbean (ECLAC). https://www.cepal.org/en/publications/45966-assessment-effects-and-impacts-hurricane-matthew-bahamas

EM-DAT, & CRED. (2022). EM-DAT: The international disaster database. www.emdat.be

FAO. (2021). *FAOSTAT statistical database.* Food Balance Sheets. https://www.fao.org/faostat/en/#data/FBS

Fu, C., Zhang, Y., Deng, T., & Daigo, I. (2022). The evolution of material stock research: From exploring to rising to hot studies. *Journal of Industrial Ecology*, *26*(2), 462–476. https://doi.org/10.1111/jiec.13195

Gallardo, C., Sandberg, N. H., & Brattebø, H. (2014). Dynamic-MFA examination of Chilean housing stock: Long-term changes and earthquake damage. *Building Research & Information*, *42*(3), 343–358. https://doi.org/10.1080/09613218.2014.872547

Geofabrik GmbH. (2021) OpenStreetMap data extracts: The Bahamas. https://download.geofabrik.de/central-america/bahamas.html

Google Earth Pro® 7.3 (2021). *Grand Bahama, 26° 39′34.01″N, 78° 31′14.34″W*. Available at: https://earth.google.com/

GovAB. (2019). *Antigua and Barbuda public building climate adaptation upgrade programme—Feasibility study final report.* Government of Antigua and Barbuda (GovAB). https://www.ctc-n.org/system/files/dossier/3b/antigua_building_adaptation_report_16072019.pdf

Government of The Bahamas. (2004). *Design and construction guidelines and plan preparation manual for subdivisions in the commonwealth of The Bahamas.* Ministry of Works & Utilities, Department of Public Works. https://www.bahamas.gov.bs/wps/wcm/connect/1ff64b64-0ba2-49cb-bd0c-1ac3285c46a4/Design+Guidelines.pdf?MOD=AJPERES

Government of The Bahamas. (2010). *First order existing land-use map of New Providence, Bahamas.* Ministry of the Environment, Department of Lands & Surveys, Department of Physical Planning, and The BNGIS Centre. https://www.bahamas.gov.bs/wps/wcm/connect/6a508224-4d98-4cdb-b4d0-41b0fe938c1c/NP_EXISTING_LANDUSE_MAP_17SEPT2010_TABLOID_FINAL.pdf?MOD=AJPERES

Government of The Bahamas. (2012). *Census of population and housing 2010.* Department of Statistics. https://www.bahamas.gov.bs/wps/wcm/connect/a6761484-9fa0-421d-a745-34c706049a88/Microsoft+Word+-+2010+CENSUS+FIRST+RELEASE+REPORT.pdf?MOD=AJPERES

Government of The Bahamas. (2016a). *Household expenditure survey 2013 report.* Department of Statistics. https://www.bahamas.gov.bs/wps/wcm/connect/5312dd47-5cd9-45f5-bf6c-dea99f3a6226/Bahamas+Household+Expenditure+Survey+2013+Report_v2.pdf?MOD=AJPERES

Government of The Bahamas. (2016b). *The national development plan of The Bahamas—Vision 2040.* [Working Draft for Public Consultation]. https://www.vision2040bahamas.org/media/uploads/Draft__National_Development_Plan_01.12.2016_for_public_release.pdf

Government of The Bahamas. (2017). *Sustainable development master plan for Andros Island [Executive Summary].* Government of The Bahamas. https://www.vision2040bahamas.org/media/uploads/AMP_EXECUTIVE_SUMMARY_FINAL_VERSION_FEB_2017__1_.pdf

Haberl, H., Wiedenhofer, D., Schug, F., Frantz, D., Virág, D., Plutzar, C., Gruhler, K., Lederer, J., Schiller, G., Fishman, T., Lanau, M., Gattringer, A., Kemper, T., Liu, G., Tanikawa, H., van der Linden, S., & Hostert, P. (2021). High-resolution maps of material stocks in buildings and infrastructures in Austria and Germany. *Environmental Science & Technology*, *55*(5), 3368–3379. https://doi.org/10.1021/acs.est.0c05642

Hashimoto, S., Tanikawa, H., & Moriguchi, Y. (2007). Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. *Waste Management*, *27*(12), 1725–1738. https://doi.org/10.1016/j.wasman.2006.10.009

He, C., Zhou, L., Yao, Y., Ma, W., & Kinney, P. L. (2020). Estimating spatial effects of anthropogenic heat emissions upon the urban thermal environment in an urban agglomeration area in East China. *Sustainable Cities and Society*, *57*, 102046. https://doi.org/10.1016/j.scs.2020.102046

Heeren, N., & Hellweg, S. (2019). Tracking construction material over space and time: Prospective and geo-referenced modeling of building stocks and construction material flows. *Journal of Industrial Ecology*, *23*(1), 253–267. https://doi.org/10.1111/jiec.12739

Huang, T., Shi, F., Tanikawa, H., Fei, J., & Han, J. (2013). Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. *Resources, Conservation and Recycling*, *72*, 91–101. https://doi.org/10.1016/j.resconrec.2012.12.013

Humanitarian OpenStreetMap Team. (2021a). HOTOSM Bahamas buildings (OpenStreetMap Export)—Humanitarian data exchange. https://data.humdata.org/dataset/hotosm_bhs_buildings

Humanitarian OpenStreetMap Team. (2021b). HOTOSM Bahamas roads (OpenStreetMap Export)—Humanitarian data exchange. https://data.humdata.org/dataset/hotosm_bhs_roads

IBRD. (2021). *Macro poverty outlook. Country-by-country analysis and projections for the developing world* (pp. 89–91). International Bank for Reconstruction and Development (IBRD), World Bank Group. https://thedocs.worldbank.org/en/doc/77351105a334213c64122e44c2efe523-0500072021/related/mpo-sm21-lac.pdf

IDB. (2018). *Action plan "Sustainable Nassau: Empowered people, revitalized city."* Emerging and Sustainable Cities Program (ESC). https://issuu.com/ciudadesemergentesysostenibles/docs/pub_2015__nassau_bhs_ces_2018

IDB. (2022a). Is it worth it to invest in resilient constructions in the Caribbean? The answer is yes! Sostenibilidad. https://blogs.iadb.org/sostenibilidad/en/is-it-worth-it-to-invest-in-resilient-constructions-in-the-caribbean/

IDB. (2022b). *The economics of climate change adaptation and ecosystem services in the Bahamas: Lessons from San Salvador Island* (2022nd ed.). Inter-American Development Bank (IDB). https://doi.org/10.18235/0004222

IMF. (2022). The Bahamas: 2022 Article IV Consultation-Press Release; Staff Report; and Statement by the Executive Director for The Bahamas. *International Monetary Fund Staff Country Reports*, *2022*(131), 85. https://doi.org/10.5089/9798400209536.002

Inostroza, L., Hamstead, Z., Spyra, M., & Qureshi, S. (2019). Beyond urban–rural dichotomies: Measuring urbanisation degrees in central European landscapes using the technomass as an explicit indicator. *Ecological Indicators*, *96*, 466–476. https://doi.org/10.1016/j.ecolind.2018.09.028

Kahhat, R., Santa-Cruz, S., & García-Torres, S. (2017). Methodology to characterize and quantify debris generation in residential buildings after seismic events. *Resources, Conservation and Recycling*, *117*, 151–159. https://doi.org/10.1016/j.resconrec.2016.11.006

Kloostra, B. (2021). *Understanding material stocks in roads at the city and multinational scale* [Thesis, University of Toronto]. https://tspace.library.utoronto.ca/bitstream/1807/109055/3/Kloostra_Bradley_202111_MAS_thesis.pdf

Knappe, F., Reinhardt, J., Bergmann, T., & Mottschall, M. (2015). *Substitution von Primärrohstoffen im Straßen- und Wegebau durch mineralische Abfälle und Bodenaushub; Stoffströme und Potenziale unter Berücksichtigung von Neu-, Aus- und Rückbau sowie der Instandsetzung (FKZ 3712 33 324).* IFEU - Institut für Energie- und Umweltforschung. https://www.bmuv.de/fileadmin/Daten_BMU/Pools/Forschungsdatenbank/fkz_3712_33_324_primaerrohstoffe_strassenbau_bf.pdf

Krausmann, F., Wiedenhofer, D., & Haberl, H. (2020). Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. *Global Environmental Change*, *61*, 102034. https://doi.org/10.1016/j.gloenvcha.2020.102034

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking stock of built environment stock studies: Progress and prospects. *Environmental Science & Technology*, *53*(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652

Lester, S. E., Dubel, A. K., Hernán, G., McHenry, J., & Rassweiler, A. (2020). Spatial planning principles for marine ecosystem restoration. *Frontiers in Marine Science*, *7*, 328. https://doi.org/10.3389/fmars.2020.00328

Martin del Campo, F., Singh, S. J., Fishman, T., Noll, D., Thomas, A., & Drescher, M. (2023). Can a small island nation build resilience? The significance of resource-use patterns and socio-metabolic risks in The Bahamas. *Journal of Industrial Ecology*, *27*(2), 491–507. https://doi.org/10.1111/jiec.13369

Merschroth, S., Miatto, A., Weyand, S., Tanikawa, H., & Schebek, L. (2020). Lost material stock in buildings due to sea level rise from global warming: The case of Fiji Islands. *Sustainability*, *12*(3), 834. https://doi.org/10.3390/su12030834

Miatto, A., Dawson, D., Nguyen, P. D., Kanaoka, K. S., & Tanikawa, H. (2021). The urbanisation-environment conflict: Insights from material stock and productivity of transport infrastructure in Hanoi, Vietnam. *Journal of Environmental Management*, *294*, 113007. https://doi.org/10.1016/j.jenvman.2021.113007

Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., & Tanikawa, H. (2017). Modeling material flows and stocks of the road network in the United States 1905–2015. *Resources, Conservation and Recycling*, *127*, 168–178. https://doi.org/10.1016/j.resconrec.2017.08.024

Ministry of Works & Utilities. (2003). *Bahamas building code—Third Edition—2003*. Government of The Bahamas. https://www.bahamas.gov.bs/wps/wcm/connect/d7ebcbad-f9b6-42e3-aff2-79f83bd91810/Bahamas%2BBuilding%2BCode%2B3rd%2BEd.pdf?MOD=AJPERES

Mycoo, M., Wairiu, M., Campbell, D., Duvat, V., Golbuu, Y., Maharaj, S., Nalau, J., Nunn, P., Pinnegar, J., & Warrick, O. (2022). Small Islands. In: H. Pörtner, D. Roberts, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, (eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2043–2121. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter15.pdf

Nasir, U., Chang, R., & Omrany, H. (2021). Calculation methods for construction material stocks: A systematic review. *Applied Sciences*, *11*(14), 6612. https://doi.org/10.3390/app11146612

Nguyen, T. C., Fishman, T., Miatto, A., & Tanikawa, H. (2019). Estimating the material stock of roads: The Vietnamese case study. *Journal of Industrial Ecology*, *23*(3), 663–673. https://doi.org/10.1111/jiec.12773

Noll, D., Lauk, C., Haas, W., Singh, S. J., Petridis, P., & Wiedenhofer, D. (2021). The sociometabolic transition of a small Greek island: Assessing stock dynamics, resource flows, and material circularity from 1929 to 2019. *Journal of Industrial Ecology*, *26*, 577–591. https://doi.org/10.1111/jiec.13206

NREL. (2015). *Energy snapshot—The Bahamas (GO-102015-4575)*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy15osti/62691.pdf

OCHA. (2020). *Natural disasters in Latin America and the Caribbean*. United Nations Office for the Coordination of Humanitarian Affairs (OCHA). https://www.humanitarianresponse.info/sites/www.humanitarianresponse.info/files/documents/files/20191202-ocha-desastres_naturales2.pdf

Ortlepp, R., Gruhler, K., & Schiller, G. (2016). Material stocks in Germany's non-domestic buildings: A new quantification method. *Building Research & Information*, *44*(8), 840–862. https://doi.org/10.1080/09613218.2016.1112096

Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., Horton, R., Knuuti, K., Moss, R., Obeysekera, J., Sallenger, A., & Weiss, J. (2012). *Global sea level rise scenarios for the US National Climate Assessment* (p. 33) Technical Report OAR CPO-1. National Oceanic and Atmospheric Administration (NOAA). https://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

Planning and Subdivision Bill. (2010). https://www.best.gov.bs/Documents/Planning-and-Subdivision-Bill.pdf

Reguero, B. G., Losada, I. J., Díaz-Simal, P., Méndez, F. J., & Beck, M. W. (2015). Effects of climate change on exposure to coastal flooding in Latin America and the Caribbean. *PLoS ONE*, *10*(7), e0133409. https://doi.org/10.1371/journal.pone.0133409

Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R. W., & Schweizer, P. (2020). Systemic risks from different perspectives. *Risk Analysis*, *42*, 1902–1920. https://doi.org/10.1111/risa.13657

Rousseau, L. S. A., Kloostra, B., AzariJafari, H., Saxe, S., Gregory, J., & Hertwich, E. G. (2022). Material stock and embodied greenhouse gas emissions of global and urban road pavement. *Environmental Science & Technology*, *56*, 24. https://doi.org/10.1021/acs.est.2c05255

Saunders, P. (2016). The 'Janet House': An endangered vernacular house form in Grenada. In R. Ahrens, F. Kläger, & K. Stierstorfer (Eds.), *Symbolism 16* (pp. 177–206). De Gruyter. https://doi.org/10.1515/9783110465938-010

Schiller, G., Müller, F., & Ortlepp, R. (2017). Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resources, Conservation and Recycling*, *123*, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007

Silver, J. M., Arkema, K. K., Griffin, R. M., Lashley, B., Lemay, M., Maldonado, S., Moultrie, S. H., Ruckelshaus, M., Schill, S., Thomas, A., Wyatt, K., & Verutes, G. (2019). Advancing coastal risk reduction science and implementation by accounting for climate, ecosystems, and people. *Frontiers in Marine Science*, *6*, 556. https://doi.org/10.3389/fmars.2019.00556

Simpson, M. C., Scott, D., Harrison, M., Sim, R., Silver, N., O'Keeffe, E., Harrison, S., Taylor, M., Lizcano, G., Rutty, M., Stager, H., Oldham, J., Wilson, M., New, M., Clarke, J., Day, O., Fields, N., Georges, J., Waithe, R., & McSharry, P. (2010). Quantification and magnitude of losses and damages resulting from the impacts of climate change: Modelling the transformational impacts and costs of sea level rise in the Caribbean. https://www.researchgate.net/publication/272791495_Quantification_and_Magnitude_of_Losses_and_Damages_Resulting_from_the_Impacts_of_Climate_Change_Modelling_the_Transformational_Impacts_and_Costs_of_Sea_Level_Rise_in_the_Caribbean

Singh, S. J., Huang, T., Nagabhatla, N., Schweizer, P.-J., Eckelman, M., Verschuur, J., & Soman, R. (2022). Socio-metabolic risk and tipping points on islands. *Environmental Research Letters*, *17*(6), 065009. https://doi.org/10.1088/1748-9326/ac6f6c

Soonsawad, N., Martinez, R. M., & Schandl, H. (2022). Material demand, and environmental and climate implications of Australia's building stock: Current status and outlook to 2060. *Resources, Conservation and Recycling*, *180*, 106143. https://doi.org/10.1016/j.resconrec.2021.106143

Symmes, R., Fishman, T., Telesford, J. N., Singh, S. J., Tan, S., & De Kroon, K. (2019). The weight of islands: Leveraging Grenada's material stocks to adapt to climate change. *Journal of Industrial Ecology*, *24*(2), 369–382. https://doi.org/10.1111/jiec.12853

Tanikawa, H., Fishman, T., Okuoka, K., & Sugimoto, K. (2015). The weight of society over time and space: A comprehensive account of the construction material stock of Japan, 1945–2010. *Journal of Industrial Ecology*, *19*(5), 778–791. https://doi.org/10.1111/jiec.12284

Tanikawa, H., Managi, S., & Lwin, C. M. (2014). Estimates of lost material stock of buildings and roads due to the great East Japan earthquake and tsunami. *Journal of Industrial Ecology*, *18*(3), 421–431. https://doi.org/10.1111/jiec.12126

Tanikawa, H., & Sugimoto, K. (2016). Chapter 3.2—Understanding tsunami damage as Lost Stock. In Y. Hayashi, Y. Suzuki, S. Sato, & K. Tsukahara (Eds.), *Disaster resilient cities* (pp. 85–97). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-809862-2.00010-3

The Bahamas Environment, Science and Technology (BEST) Commission. (2005). *The Bahamas state of the environment report: GEO Bahamas 2005*. United Nations Environmental Programme (UNEP). https://wedocs.unep.org/handle/20.500.11822/9344

The Bahamas Protected Area Fund. (2020). Bahamas protected areas fund. https://bahamasprotected.com/about/

The World Bank. (2017). *Rethinking infrastructure in Latin America and the Caribbean*. International Bank for Reconstruction and Development /The World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/26390/114110-REVISED-PUBLIC-RethinkingInfrastructureFull.pdf

The World Bank. (2020). GDP per capita (current US$)—The Bahamas. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?end=2018&locations=BS&most_recent_value_desc=true&start=2016

The World Bank. (2022a). *Population, total—Caribbean small states. World development indicators*. The World Bank Group. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=S3

The World Bank. (2022b). *Urban development. World development indicators*. The World Bank Group. https://data.worldbank.org/topic/urban-development?locations=S3

Thunshirn, P. (2020). A socio-metabolic assessment of material stocks in the electricity infrastructure. Social ecology, Working paper 187. https://boku.ac.at/fileadmin/data/H03000/H73000/H73700/Publikationen/Working_Papers/WP187_web.pdf

U.S. Department of Transportation. (2016). *Airport pavement design and evaluation* (Advisory Circular 150/5320-6F). U.S. Department of Transportation. Federal Aviation Administration. https://www.faa.gov/documentlibrary/media/advisory_circular/150-5320-6f.pdf

UNEP. (2016). *Global material flows and resource productivity. An assessment study of the UNEP international resource panel* (p. 200). United Nations Environmental Programme (UNEP). https://www.resourcepanel.org/file/423/download?token=Av9xJsGS

UN-HABITAT. (2011). *Antigua and Barbuda: St. John's urban profile*. United Nations Human Settlements Programme. http://books.google.com/books?id=F8I3_293UAEC

United Nations. (2021). *Sustainable transport, sustainable development*. Interagency report for second Global Sustainable Transport Conference. https://sdgs.un.org/sites/default/files/2021-10/Transportation%20Report%202021_FullReport_Digital.pdf

USGS. (2022). Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM courtesy of the U.S. Geological Survey. https://earthexplorer.usgs.gov/

van Zelst, V. T. M., Dijkstra, J. T., van Wesenbeeck, B. K., Eilander, D., Morris, E. P., Winsemius, H. C., Ward, P. J., & de Vries, M. B. (2021). Cutting the costs of coastal protection by integrating vegetation in flood defences. *Nature Communications*, *12*(1), 6533. https://doi.org/10.1038/s41467-021-26887-4

Verschuur, J., Pant, R., Koks, E., & Hall, J. (2022). A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards. *Maritime Economics & Logistics*, *24*, 489–506. https://doi.org/10.1057/s41278-021-00204-8

Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and expansion: Modeling material stocks and flows for residential buildings and transportation networks in the EU25. *Journal of Industrial Ecology*, *19*(4), 538–551. https://doi.org/10.1111/jiec.12216

Worldometer. (2022). Bahamas population (live). https://www.worldometers.info/world-population/bahamas-population/

Ye, L. (2022). *3D GIS modelling of road and building material stocks: A case study of Grenada* [Thesis, University of Waterloo]. https://uwspace.uwaterloo.ca/bitstream/handle/10012/18323/Ye_Lingfei.pdf?sequence=3&isAllowed=y

Yu, A. L. (2017). Food self-sufficiency and sustainable agriculture development in the Bahamas. *I-ACES: Journal of Undergraduate Research at ACES*, *3*(1), 53–57. https://www.ideals.illinois.edu/items/123022

Zhang, T., Liu, L., & Lv, X. (2019). The change in the material stock of urban infrastructures in China. *Structural Change and Economic Dynamics*, *51*, 24–34. https://doi.org/10.1016/j.strueco.2019.06.014

SUPPORTING INFORMATION

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

How to cite this article: Martin del Campo, F., Singh, S. J., Fishman, T., Thomas, A., & Drescher, M. (2023). The Bahamas at risk: Material stocks, sea-level rise, and the implications for development. *Journal of Industrial Ecology*, *27*, 1165–1183. https://doi.org/10.1111/jiec.13402