Islands at Risk

Analyzing Resource-use Dynamics from a Socio-metabolic Research Perspective

by

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Author’s Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

I am the sole author of Chapter 1, Chapter 2 and Chapter 6 of this thesis. Chapter 3, 4, and 5 are based on academic work and papers that were co-authored with other academics.

Chapter 3 has been incorporated within a paper that has been submitted for publication. The paper is co-authored by my supervisor (Dr. Simron Singh), Dr. Eric Mijts from the University of Aruba, and myself. Dr. Singh and I developed the methodology, conceptualization, and visualization of results. I carried out the collection and formal analysis of the data, as well as writing. All co-authors contributed to review and editing of the manuscript. Bibliographic citation:

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Chapter 4 has been incorporated within a paper that has been published. The paper is co-authored by Dr. Simron Singh, Dr. Tomer Fishman from Leiden University, Dr. Adelle Thomas from the University of The Bahamas, Dr. Dominik Noll from the University of Évora, and Dr. Michael Drescher from the University of Waterloo. Dr. Singh, Dr. Fishman, Dr. Noll and I developed the methodology, conceptualization, and visualization of results. I carried out the collection and formal analysis of the data, as well as writing. All co-authors contributed to review and editing of the manuscript. Bibliographic citation:

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Abstract

Our resource-use dynamics have contributed significantly to the improvement in global material standards of living through the provisioning of essential societal services. Nonetheless, these dynamics have also impacted on the already limited natural resource-base of the Earth system on which we depend. Moreover, the characteristics of a global self-perpetuating resource-use linearity, the growing demand for finite raw materials, the high waste generation that remains unrecovered, and the increasing negative effects of climate change further exacerbate the Earth system's vulnerabilities and exposure to risks. As such, the resource-use dynamics is posited as an important example of complex systems in need for better understanding, particularly in advancing towards sustainability and build system's resilience. For resource-stressed settings like small island nations, the analysis of these complex systems is not only crucial, but urgent. Small Island Developing States are often characterized by sustainability challenges like limited resource-bases, reduced waste absorption capacity, a strong dependency on external resources to meet their basic needs, geographic isolation from markets which impact connectivity and resource supply, and natural and built environment that is progressively been threatened by the negative effects of climate change, which amplify the pre-existing vulnerabilities and risks for these territories. Thus, dealing with sustainability would require a deeper understanding of the interactions and trade-offs between the resource-use dynamics and the influences that internal/external factors like climate change have over these. By doing so, the system will have the ability to both contribute to global environment change, but also determine their own vulnerability or resilience to those changes. This thesis analyzes resource-use dynamics from a socio-metabolic research perspective in the context of small islands to enhance resource security and build system's resilience, by looking into the way in which natural resources are interconnected, influenced, and managed. The analysis is spread across three main empirical Chapters, each of which contribute to advancing the arguments that arise from this work. First, in Chapter 3, the thesis analyzes the shifting resource-baselines of water, energy, and food, emphasizing the intra- and interconnected nature between essential resources and socio-metabolic risk, which builds the foundations for deeper analysis on current and future sustainability in small islands. Then, in Chapter 4, the thesis analyzes and identifies the size and make-up of material and energy flows specific to an individual case study, bringing important quantitative and qualitative insights on the potentials that reconfigured resource-use patterns may offer to minimizing or reducing socio-metabolic risk in small islands. Next, in Chapter 5, the thesis analyzes the role that critical material stocks play in driving resource-use and in furthering sustainable

development, emphasizing climate change adaptation strategies to build system’s resilience. The overall framework of this thesis has demonstrated how a better understanding of resource-use dynamics may offer an opportunity to achieve resource security and self-reliance as a resilience building measure in the island context. Finally, this thesis encourages for the development and application of holistic and long-term resource management strategies through inclusive, climate and nature-based solutions that consider the trade-offs and synergies between different resource-use dynamics.

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List of Abbreviations

AIMS. *Atlantic, Indian Ocean, Mediterranean and South China Sea*
CE. *Circular economy*
D&D. *Demolition & Discard*
DALY. *Disability-Adjusted Life Years*
DE. *Domestic Extraction*
DEM. *Digital Elevation Model*
DMC. *Domestic material consumption*
DMI. *Direct material inputs*
DPO. *Domestic processed outputs*
EEZ. *Exclusive Economic Zone*
EJ. *Exa Joules*
EoL. *End-of-life*
eUse. *Energetic use*
ew-MFA. *Economy-wide Material Flow Accounting*
FAO. *Food and Agricultural Organization*
GAS. *Gross additions to stocks*
GDP. *Gross Domestic Product*
GFA. *Gross floor area*
GIS. *Geographical Information System*
GJ. *Giga Joules*
Gt. *Giga tonnes*
HDI. *Human Development Index*
INCr. *Input non-circularity rate*
IntOut. *Interim outputs*
IRENA. *International Renewable Energy Agency*
ISCr. *Input socio-economic cycling rate*
LAC. *Latin America and the Caribbean*
LCA. *Life cycle assessment*
LDCs. *Least Developed Countries*
MFA. *Material flows accounting*
MS. *Material Stocks*
MSA. *Material stocks accounting*
MSW. Municipal solid waste
mt. *Mega tonnes*
mUse. *Material use*
NAS. *Net additions to stock*
NbS. *Nature-based solutions*
NGO. *Non-governmental organization*
NREL. *National Renewable Energy Laboratory*
ONCr. *Output non-circularity rate*
OSCr. *Output socio-economic cycling rate*
OSM. *OpenStreetMap*
PM. *Processed materials*
SAIDI. *System Average Interruption Duration Index*
SIDS. *Small Island Developing States*
SLR. Sea-level rise
SM. *Secondary materials*
SMRs. *Socio-metabolic Risks*
WEF. *Water-Energy-Food*

Chapter 1: Introduction

1.1 Background

The world’s natural capital supplies essential resources and other commodities that are fundamental to economic development and human well-being. They also support the provision of vital ecosystem services necessary for survival (Bansard & Schröder, 2021; UN General Assembly, 2015). However, our current patterns of resource use are putting sustainable growth and human wellbeing at risk. The way resources are managed, organized, utilized, and disposed is thus critical from an environmental, social, and economic perspective, and assuring the sustainability of natural resources has become one of the top priorities of the sustainability agenda (Caballero, 2015; Circle Economy, 2020; UNEP, 2016; UNEP & IRP, 2017; Vira, 2018) (see Figure 1).

Figure 1 – Direct and indirect relationship of natural resources to the three dimensions of sustainability in relation to the Sustainable Development Goals (SDGs). Adapted from: IRP (2019)

From Figure 1, we can observe that natural resources are closely linked to the UN Sustainable Development Goals (SDGs). Many of these goals are directly linked to natural resources, like SDG 1 – *End Poverty* and Target 1.4: *equal rights to economic resources, access to basic services, ownership and control over land and other forms of property, inheritance, natural resources etc*. To mention a few more, SDG 2 – *Zero Hunger* and Target 2.4: *ensure sustainable food production systems and* *implement resilient agricultural practices*, or SDG 6, SDG 7, SDG 14, and SDG 15, which directly link to the protection and improvement in the use of water, energy, marine resources, and land resources respectively. Moreover, most of these goals require a build-up of infrastructure, which requires the use of natural resources to achieve their respective goals.

Shaping the future of sustainability and achieving the global UN Sustainable Development Goals with greater confidence and certainty could be possible. Nonetheless, several aspects are crucial for the further discussion of these global objectives. One must first recognize the existing limitations in the access to or availability of natural resources worldwide, and also the minimum standards for basic human, social and economic needs which depend on natural resources. Achieving global equity and quality of life, with inclusive economic growth, reduced environmental impacts, while combating climate change and other natural resource challenges, will also demand for a better understanding of the interactions and trade-offs between the resource-use dynamics and the influences that internal/external factors like climate change have over these (UN, 2022a; UN General Assembly, 2015; UNEP, 2011; World Economic Forum, 2017). This shift towards a more sustainable way of life in our climate challenged world will require us to design the future for our society, the environment, and our natural resources as a holistic system, weighing up and balancing social, economic, and environmental goals.

We can think that societies resemble a living organism in such a sense that they demand resources and provides basic services: a living organism maintains a continuous flow of material and energy with its environment that allows its functioning, growth, and reproduction. As in every healthy living organism, those resources flows are only the minimum required to sustain and continue life. This exchange of resources, however, does not always apply in modern societies. As explained by Krausmann et al., (2016), resource-use in human societies is dynamic and in constant evolution. Through history, the needs for natural resources and with them the living standards and resources production and consumption have also evolved, going from hunter-gatherer societies to today’s industrialized societies characterized by a highly intense use of materials and energy (ibid). These dynamics pose a fact that the impacts of these resource flows have also changed (e.g., larger consumption patterns lead to an overuse and depletion of resources, as well as larger waste generation). Global material extraction has quadruple since the 1970s, from around 22 billion tonnes to 100 billion tonnes in 2020, with projections reaching around 180 billion tonnes by 2050 (Circle Economy, 2020; Krausmann et al., 2018; UNEP, 2016; UNEP & IRP, 2017). Meanwhile, the circularity rates of materials re-entering the economy at the end of their lifecycle remain low, slightly declining from 9.1% in 2018 to 8.6% in 2020 (Circle Economy, 2020). Similarly, global energy use almost tripled from 224 EJ in 1971 to 624 EJ in 2019 and is estimated to hit 879 EJ by 2050 (British Petroleum, 2021; Schandl et al., 2016; Smil, 2017, 2017; World Energy Council, 2013).

This disparity between resource-bases availability, the overexploitation and subsequent use and waste of resources portrays an unsustainable resource-use dynamic that cannot persist in the long-run, considering the limited resources available on the planet (Akenji, 2015; Steffen & Morgan, 2021). As well, the exploitation of scarce and critical resources by modern society is being intensified by a rapid economic and population growth, more resource-demanding living standards, an expanding built environment and more, especially in developing countries. Moreover, considering the intra-and interdependencies of critical resources, the increasing demand of one type of resource usually has consequences that affect different sectors due to feedback loops and trade-offs. Additionally, the challenge of meeting this growing demand is further exacerbated by climate change and an increased global complexity (IRP, 2021; UNIDO, 2010), for example:

a) The accelerated development of urbanization, rapid economic growth, and technological changes demand for resources for construction, operation and maintenance, and the growing built environment prompts concentration of population, which in turn further increases the demand of essential resources, while at the same time generating larger amounts of outflows (Allwood et al., 2011; EEA, 2015; Wehmer, 2019; Zucaro et al., 2022);
b) Extreme weather events can disrupt the built and natural environment by damaging ecosystems both on land and water, as well as damaging critical infrastructure and interrupt the supply chain, posing major threats to global and local sustainability (Rentschler et al., 2022; W. Zhang et al., 2018).
c) The adoption of intensive agriculture may alleviate food demand for that accelerated development and population nutrition needs (OECD, 2016; The World Bank, 2022n; WWF, 2022a), but in turn this production and supply chain represent the largest consumer of the world’s freshwater resources and accounts for approximately one quarter of global energy consumption (UN-Water, 2022).
d) Just the global food system alone, from food fertilizer manufacturing, to food production, harvest, transportation, processing, packaging and distribution may use a significant amount of energy and emit up to one third of all human-caused greenhouse gas emissions (Gilbert, 2012).

Given the intricate ways in which essential resources are interconnected, influenced and managed, many complex issues have confronted communities at all scales with an increasing number of challenges that affect progress towards sustainable development and that directly impact on resource security, resilience and their exposure to risk.

Overall, the concept of risk is defined as the possibility or chance of potential consequences and the severity of these arising from some action or event (e.g., human-induced, natural event, or a combination of both) (Renn et al., 2011). Individual risks describe how an event perturbs a single component in a system, while systemic risks capture the potential to inflict immediate and long-term changes on the system – including the potential cascade effect to other systems on which our society depends, especially for those living in vulnerable conditions (OECD, 2003; Sillmann et al., 2022).

Socio-metabolic risks (SMRs) could then be seen as a subset of systemic risks associated to the supply and demand, distribution, and stability of critical resources in a socio-ecological system. Maladaptive and climate-insensitive development practices amplify the system's vulnerabilities and reduces its resilience to shocks and changes (Singh et al., 2020, 2022). These dynamics should also be understood through the amplification of risks due to the compounding effects of multiple hazards happening simultaneously or sequentially that trigger cascade effects and affect other components of the system, which puts development needs in jeopardy (Franzke et al., 2022; Klose et al., 2021). In this sense, countries all over the world, and especially resource-stressed systems like small islands, are striving towards sustainable development by addressing structural and external challenges aimed at minimizing and reducing SMRs, at enhancing resource security and building system's resilience through supporting natural resource management, as well as prevention of and adaptation to climate change.

1.2 The context of Small Island Developing States (SIDS)

SIDS are a distinctive group of developing countries and territories facing unique social, economic, and environmental challenges, which serve as obstacles for sustainable development (UN-OHRLLS, 2013, 2015, 2022). These countries are distributed in three regions across the globe: the Caribbean, the Pacific, and the Atlantic, Indian Ocean, Mediterranean and South China Sea (AIMS). More than 65 million people live in these territories, slightly less than 1% of the global population (UN-OHRLLS, 2013), and the highest number of SIDS is in the Caribbean region (United Nations, 2022a).

Overall, SIDS experience considerable adversities that require special cross-sectoral assistance to achieve sustainable development and internationally agreed goals. These were highlighted in The

Barbados Programme of Action of 1994 (United Nations, 1994), and the comprehensive review of the BPOA - Mauritius Strategy of Implementation of 2005 (United Nations, 2005). Included in these adversities are the need to mobilize internal and external sources to meet the challenges of sustainable development and capacity-building, the need to ensure better and more efficient use of official development assistance, the need for better regional coordination of effort and improved access to public and private financial and technical resources, and the need to develop human resources, among others. Both documents showcased that the difficulties that SIDS face in their path towards a sustainable development are particularly complex and severe. Once more, these adversities were reiterated during the third UN SIDS summit held in September 2014, where Heads of State and Government and high-level representatives officially incorporated the SIDS Accelerated Modalities of Action (SAMOA) Pathways in their agendas (UN-OHRLLS, 2014).

SIDS are also characterized by an array of sustainability problems such as heavy dependence on imports that causes elevated costs of basic supplies primarily due to a limited resource-base, poor connectivity and high costs of crossing open sea, which function as stressors over essential resources. Together with a reduced waste absorption capacity, and relatively high population densities, this causes more pressure on their usually limited domestic markets. Moreover, SIDS have been identified as the most vulnerable to the negative impacts of climate change around the world (IPCC, 2007), which increasingly aggravates their resource security levels. Additionally, the negative effects of climate change such as sea-level rise and extreme weather events result not only in infrastructure losses but also in the immediate loss of critical services and damage to socio-economic and cultural infrastructure. Restoring the services provided by these stocks comes with large material requirements for reconstruction, oftentimes incurring huge debts (EM-DAT & CRED, 2022; UNFCCC, 2007). Their relative isolation or remoteness, vulnerability to environmental threats, and exposure to frequent and intense natural hazards aggravated by the effects of climate change make them especially susceptible to shocks (UN-OHRLLS, 2022). Thus, resource management, risk management and climate change adaptation are key to protect the sustainable development of island systems.

1.2.1 SIDS vulnerabilities

With a limited and unequal distribution of natural resource-base, growing trends in resource demand, rapid urbanization and other complex social and climate pressures, the overall resource security and sustainability in SIDS are under threat. SIDS are at a very high risk of anthropogenic groundwater pollution (UN, 2022b; UNESCO-IHP & UNEP, 2017), and expected to experience freshwater stress in the future (Gheuens et al., 2019; IPCC, 2018), especially in Caribbean SIDS (Dubrie et al., 2022; Willaarts et al., 2014). Moreover, with small domestic markets, SIDS, including Caribbean SIDS, rely on imports of critical resources such as materials for construction, fossil fuel for energy generation, food, and miscellaneous commodities of up to 80-90% of their requirements (Bradshaw et al., 2020; Dorodnykh, 2017; ECLAC, 2016; FAO, 2019; IRENA, 2014; Symmes et al., 2019; UNESCO, 2017, 2017). Additionally, imports dependency makes SIDS highly vulnerable to price fluctuations and resource availability, thus impacting on resource security (UN-OHRLLS, 2013).

SIDS are on the frontlines of climate change despite having made a very small contribution to the overall global carbon emissions (IISD, 2021). Impacts from climate change are already being experienced by most SIDS, hampering the efforts to transition into a more sustainable future (IMF, 2021; Sachs et al., 2021; Thomas et al., 2020). SIDS are consistently ranked high on various vulnerability indices (Aleksandrova et al., 2021; Atkins et al., 2000; The Commonwealth Secretariat, 2021). SIDS represent over 30% of countries with the highest relative annual losses due to disasters (OECD & The World Bank, 2016). Globally, there were 434 climate related disasters (storms, floods, and droughts) in Caribbean, Pacific, and Atlantic, Indian Ocean, Mediterranean and South China Sea (AIMS) SIDS combined between the years 2000 and 2021. These resulted in over 10,000 deaths, close to 40 million affected persons, and close to 130 billion USD in damages (see Table 1 showing breakdown of disasters by type of event and by SIDS region).

Table 1 - Climate-related disasters in all SIDS by region and by type of event, between 2000 and 2021.

Type of event	SIDS Region	Storm	Flood	Drought	All
Number of events	Caribbean	173	86	13	272
	Pacific	75	44	14	133
	AIMS	13	12	4	29
Deaths	Caribbean	5,445	3,957	N.D.	9,402
	Pacific	477	147	24	648
	AIMS	26	33	N.D.	59
People affected	Caribbean	25,859,224	4,060,635	4,826,545	34,746,404
	Pacific	2,075,255	595,804	286,814	2,957,873
	AIMS	408,972	353,963	232,000	994,935
Damage (Thousand USD)	Caribbean	124,420,275	579,550	N.D.	124,999,825
	Pacific	1,924,699	295,797	74,197	2,294,693
	AIMS	87,398	8,227	N.D.	95,625

Source: EM-DAT & CRED (2022). N.D.= No Data

Compared to other regions, the Caribbean SIDS show higher impacts on livelihoods and damage due to climate-related disasters. This correlates with the World Risk Reports, which places Caribbean SIDS among the top 30 countries from a list of close to 200 countries around the world in terms of exposure and vulnerability to risks (Aleksandrova et al., 2021). As one of the most disaster-prone regions in the world (The World Bank, 2017), many storms (including 11 Category 4 and 5 hurricanes), floods and droughts have affected the region between the years 2000 and 2021, directly or indirectly impacting more than 30 million inhabitants (see Table 1). Moreover, in 2017 Hurricane Maria and Hurricane Irma caused loss of lives and massive widespread infrastructure damages which amounted to more to almost 90 billion USD, surpassing the cumulative 71.7 billion USD of GDP for the Caribbean SIDS in that same year (EM-DAT & CRED, 2022; OCHA, 2020; The World Bank, 2020). Annual damages to infrastructure resulting from natural disasters in the Caribbean region are estimated at 0.5-1 billion USD per year (Bettencourt et al., 2021). These damages result not only in material losses, but also in the immediate interruption of critical services and in the generation of large affluents of waste that are usually not properly disposed of. As an example, back in 2017, the Caribbean Island of Saint Martin suffered from the impacts of hurricane Irma. The intensity of the waste streams was of such magnitude, that even three years after the event, post-Irma waste management operations were still carried out (Popescu et al., 2020)

Looking at SIDS and the spatial perspective, there is the possibility of “prototypes” of sustainability management being readily applicable at the multilevel scale, aiding at coordinating between all levels of governance to properly manage resources. Islands could become learning regions or niches of innovation where we could find alternative ways for greater system transformation. These spaces are important because they allow the experimentation, the interaction with similar islands in close proximity, sharing knowledge and generating connections that could pave the way towards the implementation of novel policies, plans, and projects towards building resilience and resource security (Gibbs & O’Neill, 2017; Healy & Morgan, 2012; Truffer & Coenen, 2012; Westley et al., 2011). As such, SIDS may be considered as a potential model for the upcoming future and are an excellent focal point to study the interactions and trade-offs between the resource-use dynamics and the influences that internal/external factors like climate change have over these.

1.3 Purpose, questions, and objectives

Resource use patterns can embody systemic risks and cascade effects which in turn inhibit the socioeconomic system’s ability to deliver critical services necessary for survival. Certain maladaptive and climate-insensitive development practices amplify the system’s vulnerabilities and risks. This can be caused by individual or compounding effects of multiple hazards happening simultaneously or sequentially that trigger cascade effects and affect other components of the system. This in turn puts development needs in jeopardy and reduces the system's resilience to shocks and changes (Franzke et al., 2022; Klose et al., 2021), especially for resource-stressed systems like small islands. Recognizing the systemic nature of these challenges, and with the support of science-based research and policies, this study can play a key role in helping communities design strategies to reduce local vulnerabilities while transitioning to a more sustainable and resilient future.

The overall purpose of this doctoral study is to explore the dynamics of socio-economic metabolism in the context of Caribbean SIDS to enhance resource security and build system's resilience by looking into the way in which essential resources are interconnected, influenced, and managed. While Chapters 3, 4, and 5 of this study are guided by their own research objectives and questions, this study seeks to answer the following overarching research questions:

1) ***Which characteristics of the dynamics of resource-use exacerbate or alleviate SMRs in the island context?***

2) ***How could the dynamics of resource-use be influenced to advance in the transition to a sustainable, resilient, and resource-secure island system?***

Within this context, the main objectives of the study are as follows:

a) Establish intra- and interdependencies of essential resources and potential SMRs through the identification and measurement of the scale and composition of critical resources in the island system
b) Determine the internal and external characteristics of the dynamic island system that influence over SMRs and cascade effects
c) Highlight potential development strategies to enhance resource security, to build system's resilience, and to prevent and adapt to climate change

1.4 Organization of the thesis

This study follows an integrated format that includes a compilation of 6 Chapters, of which three are comprised of standalone empirical articles that link and build upon each other.

The Introduction, Chapter 1, provides an overview of the research problem with a focus on the relevant background and the context of small island developing states. It also presents the overall purpose, as well as overarching research questions and objectives, and an outline of the structure of the study.

The Methods, Chapter 2, offers an up-to-date review of the relevant literature relevant to this study's purposes, emphasizing its significance in the context of small islands. It highlights the idea of resources interconnectedness and the importance of these to accounted for in sustainability and resilience. This Chapter 2 describes the main fields of research to studying society–nature interactions at different spatiotemporal scales: Socio-metabolic Research and Industrial Ecology. To understand resource-use dynamics and socio-metabolic risks, Chapter 2 describes tools and concepts such as resources flows and stocks accounting, circular economy, and the water-energy-food nexus. Both Chapter 1 and 2 provide an overarching structure in which this problematic is framed and briefly contextualize the articles within the broader study from a Socio-metabolic Research Perspective.

The first empirical article, Chapter 3, is linked to all three main objectives. For the most part, this Chapter aligns to the first overarching research question of ***which characteristics of the dynamics of resource-use exacerbate or alleviate SMRs in the island context?*** and to a lesser degree on ***how could the dynamics of resource-use be influenced to advance in the transition to a sustainable, resilient, and resource-secure island system?*** It offers a regional and country-specific quantitative and qualitative review of the past, current, and future trends of critical resources for a group of Caribbean SIDS. It discusses the main commonalities and differences in these island's resource-bases, specifically of the resources water, energy, food, and their nexus. This Chapter emphasizes the interdependence of resources and how a specific combination of resource-use could result in SMRs, which can lead to long-term inadequate coping and adaptive capacities to face systemic risks. Simultaneously, it is argued that a better understanding of these resource-use dynamics and SMRs may improve resource security and resilience by identifying potential barriers and openings for positive transformative change. In this empirical study, the resources intra- and interdependencies and potential SMRs were analyzed, serving as a foundation to continue exploring the resource-use dynamics in the island context.

The second empirical article, Chapter 4, is linked to all three main objectives and the two overarching research questions of ***which characteristics of the dynamics of resource-use exacerbate or alleviate SMRs in the island context?*** and ***how could the dynamics of resource-use be influenced to advance in the transition to a sustainable, resilient, and resource-secure island system?*** Narrowing the scope to a single island case study (The Bahamas), this study adopted an Economy-wide Material Flow Analysis framework, complemented by the Circularity accounting framework, to monitor the island's biophysical system, aiming at describing the metabolic profile, and identifying SMRs, cascading effects and potentials for building circularity and resilience of the case study. In this Chapter, the interdependence between socio-economic sectors driving the demand for resources was investigated, and the analysis provided consistent estimations for current metabolic levels in the case study. Here, it is demonstrated the importance that knowledge over the scale and composition of critical resources has for reconfiguring resource-use patterns to minimize SMRs in the island context.

The third empirical article, Chapter 5, is also linked to all three main objectives and the two overarching research questions of ***which characteristics of the dynamics of resource-use exacerbate or alleviate SMRs in the island context?*** and ***how could the dynamics of resource-use be influenced to advance in the transition to a sustainable, resilient, and resource-secure island system?***. Expanding on the understanding of resource-use dynamics and socio-metabolic risks, this Chapter analyzes the same island case study (The Bahamas). A Geographical Information System (GIS)-based spatial Material Stock Accounting analysis is applied to identify material stock dynamics and their vulnerability to the effects of climate change, highlighting some of the external factors influencing over resource security and resilience. It also touches upon the compound and cascade effects that impact on other system's components, such as in the built and natural environment, society and the economy. The results allow us to inform on present infrastructure stock and prospective future demands for construction materials, as well as advise the direction of future resilient development strategies, in addition to measuring and mapping essential infrastructure threatened by sea level rise.

Finally, Chapter 6 provides a review of the findings and major conclusions, a discussion on the implications and contributions resulting from the entire research project, as well as suggestions for further research.

Chapter 2: Review of relevant literature in the island context

2.1 Industrial ecology and socio-metabolic research

The development trajectory of a socio-economic system relies on biophysical flows and stocks and the social structures that support these. The way resources are managed, organized, utilized, and disposed is thus critical from an environmental, social, and economic perspective. To understand how best this can be achieved requires a critical analysis of societies, natural systems, and their dynamics (Haberl et al., 2004; Wiedenhofer et al., 2016). Nonetheless, a system's thinking and holistic analytical reasoning is necessary for the pursuit of these goals. A narrow view in such complex island systems can often lead to simply moving a problem from one place of the system to another without any net gains. Hence, it is important to develop a broad perspective on the resource-uses, as well as the dynamics that occur within and outside the social structure that harness them to function properly (Pauliuk, 2018).

Industrial Ecology is a multidisciplinary field of research that focuses on proposing sustainable solutions to human development, combining natural, technical, and social sciences in a system view. It considers complex human systems in concert with natural systems and strive to limit the environmental impacts while recognizing the importance of socio-economic factors in achieving those solutions (IS4IE, 2022). In words of Donella Meadows, "once we see the relationship between structure and behavior, we can begin to understand how systems work, what makes them produce poor results, and how to shift them into better behavior patterns" (Meadows, 2009).

At the core of the industrial ecology field is the Socio-metabolic research framework. Its inherent strength lies in taking society as unit of analysis, interpreted as a socio-metabolic system in which systems (e.g., natural or biophysical, economic, and others) interact at different spatio-temporal scales, influencing particularly on the social activities which have a direct material impact on the ecosystem (Fischer-Kowalski, 2011; Wiedenhofer et al., 2016). Its core goal is to systematically account for flows of biophysical resources associated with defined social systems or their components, in other words, flows between nature and society, between different societies, and within societies, playing a pivotal role in understanding human-nature interactions (Haberl et al., 2019).

Industrial ecology and its core element of socio-metabolic research are highly relevant in the island context. They serve to identify the dynamics of resource-use and supports distinct sustainable resource-use patterns aimed at replicating the efficient flow of materials and energy as in nature. It explores the potential for urban mining, where resources from the anthropogenic material stocks embodied in unused infrastructure could be reclaimed, giving them a new purpose instead of depositing them on space-consuming dump sites. This approach modifies the concept of resources “waste” into “unused” resources and touches upon the principles of circular economy and nature-based solutions to enhance system resilience. This approach could also be key in sustainability science by delivering consistent analysis on the biophysical and socio-economic systems and connecting processes that help to further understand the dynamics of resource-use and human-nature interactions.

2.1.1 Resources flows and stocks accounting

Industrial ecology and socio-metabolic research include a broad range of methods approaches for measuring, analyzing, and modeling society’s use of biophysical resources: life cycle assessment (LCA), which is a systemic analysis of flows and the related environmental impacts associated with all the stages of a product or service’s life (Muralikrishna & Manickam, 2017); input and output analysis, which aid in quantifying various footprint indicators for a large number of products and sectors based on the exchanges within and between countries and the environment (Giljum et al., 2015); industrial symbiosis, which engages traditionally separate entities in a collective and synergistic approach of competitive advantage involving physical exchange of materials, energy, water, information, and by-products (Boons et al., 2011; M. R. Chertow, 2000); material flows accounting (MFA) and material stocks accounting (MSA) together track the flows, stocks, and losses of materials in a specific system (European Commission, 2018; Graedel & Lifset, 2016).

Current socio-metabolic research views a socio-economic system as a system of material throughput (flows of material), where a large part of materials accumulates over time (stocks of material) as part of the built environment to deliver critical services to society. The more stocks, the more flows are required to maintain the stocks. As such, there has been an increasing interest in approaching economic development and sustainability through resources flows and stocks accounting as these are among the most important indicators available for monitoring changes in the patterns and rates of resource use as economies grow (UNEP & IRP, 2022). By means of measuring the volume and composition of materials that flow through an economic system we can determine the scale and rate of resources consumption within a society, and this can serve as a proxy to identify potential environmental impacts and opportunities for further development. Moreover, as the built environment stocks constitute the majority of anthropogenic material stocks in terms of the mass (Krausmann et al., 2020), these serve as potential reservoirs of secondary materials. In parallel, material stock types and distributions determine the ability to provide certain services that our society rely on. Identifying and mapping location and distribution of stocks is also critical considering future climate change scenarios.

In recent years with the rising concerns over material and energy flows through society, there has been several methodologies that try to analyze infrastructure development using transdisciplinary lens. As described by Augiseau and Barles, stock-flow studies of construction materials can be broadly categorized in 4 main purposes: "a) forecasting and comparing future input and output flows, b) studying the influence of several parameters on future flows, c) estimating the present or future stock as well as its evolution, d) studying urban metabolism and analyzing the interaction between flows and stocks (Augiseau & Barles, 2016). Previous research has demonstrated the value of material stocks and flows accounting as an innovative means of measuring levels of socio-economic metabolism in the context of small islands. Most socio-metabolic research has focused on inflows (e.g. Bahers et al., 2022; M. R. Chertow et al., 2020; Eisenhut, 2009; Krausmann et al., 2014; Rahman et al., 2022; Schulz, 2007; Singh et al., 2001), very few on biophysical stocks (e.g. Bradshaw et al., 2020; Liu et al., 2022; Noll et al., 2019; Symmes et al., 2019) and outflows (e.g. M. Eckelman & Chertow, 2009; M. J. Eckelman et al., 2014; Elgie et al., 2021; Mohammadi et al., 2021; Sarkar et al., 2011), while only one uses a mass-balanced approach to explore the potential for a "circular economy" in an island context (Noll et al., 2021). These studies have generated only a partial view of the complex socio-economic metabolism dynamics. Thus, incorporating the material stocks and flows accounting into this study holistically, could give us further insights on the interrelations between material and energy flows, socio-economic activities, the services provided by these combinations of stocks/flows, and external characteristics influencing over these dynamics.

2.1.2 Circular economy

An approach that is gaining momentum to address sustainability and resource-related challenges is the concept of Circular Economy (CE) (United Nations, 2021b). CE departs from the dominant linear (take-make-dispose) economy in favor of a relatively closed, systemic, cyclical, and restorative model. CE is aspirational in that it seeks to borrow the idea of cycling resources through our society just as nature cycles water, nutrients, carbon, and other essential materials (Ekins et al., 2019). CE features the important word "economy", which carries with it the necessity of livelihoods, provisions, and the responsible allocation of scarce resources. Because islands are resource-constrained by size, relative isolation, and a lesser range of local material diversity, CE has special resonance in the island context.

Recent reviews have revealed that current CE research and practice tend to focus on resource life-extending strategies and the eco-efficiency of products and services (e.g. reducing resource input per unit of output) (Alhawari et al., 2021; Arruda et al., 2021; Corona et al., 2019). Economic and environmental benefits are the primary motivations for more efficient product design, cleaner production, and closing material loops by valorizing waste streams (Gusmerotti et al., 2019; OECD, 2020b). In order to move towards a sustainable, low-carbon, and resource-efficient economy, and to understand SMRs and trade-offs between sectors, efforts are needed to conduct CE research at the macro- or economy-wide level.

However, only very few studies exist that describe the physical material flows and the interactions of the economy with the natural environment and other economies while drawing from circularity principles. For example, the economy-wide CE in the EU28 and in Austria for the year 2014 (Jacobi et al., 2018; Mayer et al., 2019), the study on the scale and circularity of global socio-economic flows through the global economy over the past century (Haas et al., 2020), and the work from the circularity gap reporting initiative showing the volume of globally extracted resources per year and final destination of outflows (Circle Economy, 2020).

In the island context, CE studies are even more scarce. A study on circular flows of plastics for Trinidad & Tobago highlighted a typical challenge for island nations: the import of materials with limited domestic demand at the end-of-life (Millette et al., 2019), and a study on circularity potentials of Grenada’s waste management system showed that waste flows are rapidly approaching tipping points that threaten social, environmental and economic health (Elgie et al., 2021). While it has been highlighted that waste is an outflow that is not properly managed (Mohammadi et al., 2021), Noll et al. (2019, 2021) has looked into island-wide circularity potentials in the context of the Greek island of Samothraki from the years 1929 to 2019.

To bring deeper systemic transformations, the linear metabolism of “take-make-dispose” that many SIDS exhibit could be changed into a plan of action with circularity as one of its core elements, where focus is given on reducing material use, redesigning materials to be less resource intensive and recycling waste as input to manufacture new materials and products (Island Innovation, 2019; US EPA, 2021). For islands to transition to policies in favor of a resource-secure, resilient, and sustainable system, an economy-wide CE approach is needed. Thus, CE has both an element of environmental sustainability and the potential to enhance the quality of island life (Saavedra & Alleng, 2020).

2.1.3 Water-Energy-Food Nexus

The Water-Energy-Food (WEF) Nexus concept emerged in the international community in response to climate change and many complex social changes. Issues such as population growth and resources scarcity are putting more pressure on critical resources such water, energy, and food, presenting communities with an increasing number of trade-offs and potential conflicts among these resources that have intricate interactions. Future Earth states that there is a need to provide knowledge "to understand how interactions between water, energy and food are shaped by environmental, economic, social and political changes and how the synergies and trade-offs among them can be better planned and managed" (Future Earth, 2022). This concept aims to identify the interactions and connections between those three resources, the tradeoffs, and synergies (mutually beneficial outcomes) of water, energy, and food systems, internalize social and environmental impacts, and guide development of cross-sectoral policies. Moreover, the nexus affects the extent to which water, energy and food security objectives can be simultaneously achieved (Ferroukhi et al., 2015).

According to Albrecht, Crootof, and Scott (2018), the nexus can serve as a) an analytical tool utilizing an array of different approaches such as Integrated Assessment Models (Howells et al., 2013), Material Flow Analysis (Villarroel Walker et al., 2014) , Life Cycle Analysis (R. H. Mohtar & Daher, 2014), or Sankey Diagrams (Mukuve & Fenner, 2015), among others, with distinct marked emphasis on a particular or combined resource; b) a conceptual framework, aiming at understanding the different resources implications; and c) a discourse for problem framing and cross-sectoral collaboration (Keskinen et al., 2016).

Due to the complexity of the problematic, the water-energy-food nexus is typically studied from a specific angle, addressing partial interlinkages and with a limited focus on the governance issues of the resources (Theesfeld, 2018). There have been several studies that have looked at the interlinkages between WEF in an exploratory context (Asian Development Bank, 2013; Daher & Mohtar, 2012; Leck et al., 2015; UN-ESCAP, 2013), some other studies have presented an overview evaluation of these resources on different spatiotemporal levels, such as in Asia-Pacific, Europe, and Latin America and the Caribbean (LAC) (Magnana et al., 2019; Mahlknecht et al., 2020; Taniguchi et al., 2017), and some others have presented more specific case-studies on the water-energy-food accounting, such as in Mauritius, South Africa, Southern Africa, Egypt, and the Indian State of Punjab (El-gafy, 2017; Giampietro et al., 2013; Nhamo et al., 2018). Others have analyzed a nexus coupled with more emphasis in other elements besides water-energy-food, such as with ecosystems, land, or climate change (Ferroukhi et al., 2015; Hoff et al., 2013; UNECE, 2015).

In the island context, WEF nexus studies remain limited. The water-energy nexus was considered as a means to generate energy from tidal power on Orkney Island (Scotland), and desalinizing water using solar energy was studied for Mauritius and the Canary Islands (UN Sustainable Water and Energy Solutions Network, 2020). The energy-food nexus was studied for 14 selected Micronesia, Melanesia and Polynesia Pacific island countries with the aim to connect bioenergy and food security (Chapman, 2009). Vourdoubas (2020) studied the nexus between agriculture and renewable energies in the island of Crete, Greece. The water-food nexus was recently discussed at the 2020 World Water Week exploring how freshwater management can contribute to food and nutrition security on small island states (FAO & Vrije Universiteit Amsterdam, 2020).

With respect to the Caribbean, Daw and Stout (2019) were concerned about strategies to counter energy, water and food shortages caused by extreme weather events on the island of St. Eustatius, a municipality of the Netherlands. Similarly, Beatty (2015) analyzed The Bahamas to become energy, water and food secure. van der Geest and Slijkerman (2019) published an introductory factsheet of the WEF-nexus for Bonaire, another island municipality of the Netherlands, and what might be potential nexus interventions. Jia (2019) explored the social and environmental performances based on threshold values (including WEF) of five Caribbean island nations aiming at reducing their metabolic stress. As well, Mahlknecht et al. (2020) performed one of the first WEF-nexus studies in the Caribbean, examining the baseline and trends of these essential resources. The most complete study to date on the WEF-nexus analysis for Caribbean SIDS was performed by Winters et al. (2022), where an evaluation of sustainability under current conditions was performed. Considering the special characteristics of SIDS, through analyzing the WEF nexus, one could establish a solid foundation on the interconnected nature of resources and external factors influencing over these, enhancing our understanding of the socio-economic metabolism, which is important for planning and sustainable development especially in the island context.

2.2 Socio-metabolic risks

Systemic risks are those associated with cascading impacts that spread within and between systems at all scales (e.g., global, national, regional, local) and sectors via the flow of people, goods, capital, and information within and across the system boundaries. Depending on how the elements of the affected system interact with each other, either through positive or negative feedback processes, the levels of system resilience can be impacted, which can lead to potentially existential consequences and system collapse across a range of time horizons (Sillmann et al., 2022). Thus, risk science provides a perspective that enables integrated analysis of all dimensions of resilience (Logan et al., 2022). In the context of socio-metabolic research, Singh et al. (2022) considers socio-metabolic risks (SMRs) as a sub-set of systemic risks and defines them 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 this sense, specific resource dynamics can entail SMRs and cascade effects, which in turn inhibit progress towards greater resource security, self-reliance, and the system’s ability to continue delivering societal services necessary for survival (ibid).

In the international agenda, SIDS are recognized as being continuously grappling with the effects of SMRs, some of which have been exacerbated by sea-level rise and other adverse impacts of climate change, which affect their survival and viability and impede their progress towards sustainable development (Bettencourt et al., 2021; OECD & The World Bank, 2016; UN, 2010; United Nations, 2015; UN-OHRLLS, 2014). Case-studies in the context of small islands, although not explicitly framed as SMRs, have highlighted the interaction of different resource feedback processes and their impacts on the system. Some have explored how certain resource management strategies can impact on resource security on SIDS (FAO & Vrije Universiteit Amsterdam, 2020). Chapman, (2009) highlights the urgent need to put in place an integrated resource security policy framework and strategies that consider the existing resource-bases in pacific islands. The author warns that failing to do so could lead to the system instability and impact on resource security. Bradshaw et al., (2020); Merschroth et al., (2020); and Symmes et al., (2019) quantified the material stocks for Antigua & Barbuda, Fiji, and Grenada, respectively. The authors included in their analysis potential SMRs in infrastructure and planning under different sea-level rise scenarios. Noll et al., (2021) accounted for the biophysical basis of the Greek island of Samothraki, highlighting the complex interactions between environmental, economic, and social factors in the island. Daw and Stout (2019) advised to assess and prepare for the impact of extreme events by strengthening critical and exposed sectors on the island of St. Eustatius. Winters et al., (2022) analyzed the resource-bases of essential resources in Caribbean SIDS and estimates future impacts on sustainability under current trends.

The exploration of the concept of SMRs has been investigated through different perspectives (WEF-Nexus, circularity principles, material flows and stocks accounting, climate change, etc.) Although these have shown promising results in addressing some pressuring issues related to resource-use dynamics, there seems to be a limitation at integrating the interactions between resources and external factors and at explicitly identifying associated SMRs and cascading effects within and across sectors, especially in an island context. Thus, effectively, and clearly identifying SMRs could serve as leverage points to articulate adaptation strategies and for building resource security and system's resilience. Understanding these resource-use dynamics could aid in securing a sustainable and stable supply of resources and services in the island system.

2.3 General considerations

The fieldwork component for primary data collection could not take place as a consequence of the COVID-19 pandemic and the ban on research travel, which posed significant difficulties to collect the necessary data for this analysis. This situation was compensated by adapting the research with a plan to gather data remotely, through contacting government officials and non-governmental organizations, through consulting international and national statistical databases, and through reviewing independent studies and reports, among others. The Methods section for Chapters 3, 4, and 5 provide further details on data sources and compilation methodologies.

The analysis of Chapter 3 (the water, energy, food nexus) and Chapter 4 (material flows) are not dependent on location. On the other hand, Chapter 5 (material stocks) is dependent on location. The analysis of the case study and the spatial component of Chapter 5 is covered through the utilization of Geographical Information Systems, which indicates the georeferenced location of the individual material stock, as well as the affectation by sea-level rise.

Chapter 3: The resource (inter)dependency of critical resources in small islands from a socio-metabolic risk perspective[1]

3.1 Abstract

Socio-metabolic risks (SMRs) are systemic risks associated with the availability of critical resources, the integrity of material circulation, and the distribution of their costs and benefits in a socio-ecological system. For resource-stressed systems like small island nations, understanding trade-offs and synergies between critical resources is not only crucial, but urgent. Climate change is already putting small islands at high risk through more frequent and intense extreme weather events, changing precipitation patterns, and threats of inundation with future sea-level rise. This Chapter compares the shifting resource-baseline for 14 Caribbean island nations for the year 2000 and 2017. It analyzes water, energy, and food (WEF) and their nexus through the lens of SMRs, using indicators related to their availability, access, consumption, and self-sufficiency. The findings of this Chapter point to the decreasing availability of all three resources within the Caribbean region. Meanwhile, between 2000 and 2017, consumption levels have increased by 20% with respect to water (from 230 to 275 m^3/cap/yr) and primary energy (from 89 to 110 GJ/cap/yr), and 5% for food (from 2,570 to 2,700 kcal/cap/day). While universal access to these resources increased in the population, food and energy self-sufficiency of the region has declined. Current patterns of resource-use, combined with maladaptive practices, and climate insensitive development – such as coastal squeeze, centralized energy systems, and trade policies - magnify islands' vulnerability. Disturbances, such as climate-induced extreme events, environmental changes, financial crises, or overexploitation of local resources, could lead to cascading dysfunction and eventual breakdown of the biophysical basis of island systems. The analysis performed in this Chapter is a first attempt at operationalizing the concept of SMRs, and offers a deeper understanding of risk-related resource dynamics on small islands, and highlights the urgency for policy response.

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[1] The contents of this section of the Chapter have been incorporated within a paper that has been submitted for publication. Martin del Campo, F., Singh, S. J., Mijts, E. (2023). "The resource (in)sufficiency of the Caribbean: Analyzing socio-metabolic Risks (SMR) of Water, Energy, and Food". Submitted to *Frontiers in Climate*. Submission date: October 31, 2022. Minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

3.2 Introduction

The international community is tasked with solving a set of intricate and interdependent issues directly linked to the management of essential resources such as water, energy, and food (de Amorim et al., 2018; UN General Assembly, 2015). Complex social changes (e.g., population growth, rapid urbanization, resource scarcity and increase in consumption, among others) are putting increasing pressure on these resources (Endo et al., 2015; Spiegelberg et al., 2017), which impact on overall global resource security and sustainability. The water-energy-food (WEF) nexus seeks to understand the (inter)dependency, synergies, conflicts and trade-offs between water, energy, and food and the way these resources are shaped by our global resource system (De Laurentiis et al., 2016; FAO, 2014; Future Earth, 2022; G. B. Simpson & Jewitt, 2019). Moreover, the nexus explores the extent to which the water, energy and food objectives from the Sustainable Development Goals (SDGs) 2, 6, and 7 can be simultaneously achieved (Ferroukhi et al., 2015; R. Mohtar, 2016). Given the intricate WEF interactions, many complex issues have confronted communities at all scales with an increasing number of challenges that affect progress towards the SDGs and that directly impact on resource security and resilience, especially for SIDS.

SIDS are often characterized by their narrow resource base, small size, remoteness, high dependence on imports, and their vulnerability to extreme weather events and external shocks, among others (Deschenes & Chertow, 2004; UNCTAD, 2021). Impacts from climate change are already being experienced by most SIDS, hampering the efforts to transition into a more sustainable future (IMF, 2021; Sachs et al., 2021; Thomas et al., 2020). SIDS are at a very high risk of anthropogenic groundwater pollution (UN, 2022b; UNESCO-IHP & UNEP, 2017), and most are already experiencing freshwater stress due to increasing demand and decreasing supply (Gheuens et al., 2019; IPCC, 2018). Average energy rates are higher than in other regions (IRENA, 2019) and they depend on imported fossil fuels for up to 90% of their energy needs (UNEP, 2014a). Similarly, SIDS are primarily net food-importing countries with low domestic food production, which makes them highly vulnerable to price fluctuations and availability, thus impacting on food security (Dorodnykh, 2017; FAO, 2019, 2020b, 2021c; UN-OHRLLS, 2013).

The decoupling of island economies from their natural environment is characteristic of SIDS, and their reconnection is a precondition for island sustainable development (M. Chertow et al., 2013). For SIDS, a combination of distinct resource-use patterns, demographics, maladaptive and climate-insensitive models of development, and the adverse effects of climate change have led to compounding shocks and weak coping and adaptive capacities to face systemic risks, which often amplify pre-existing system's vulnerability levels and sustainability challenges, and reduces its resilience to shocks and changes (IMF, 2021; Sachs et al., 2021; Thomas et al., 2020). Thus, water, energy, and food can be regarded as interdependent and essential resources in need of a sustainable management approach that maximizes resource-security, improves the linkages within the nexus, and reduces inherent systemic risks.

This Chapter compares the shifting resource-baseline for 14 Caribbean SIDS during the years 2000 and 2017. It analyzes three critical resources: water, energy, and food and their nexus, focusing on the dimensions of availability, access, consumption, and self-sufficiency. These findings are discussed through the concept of SMRs described as those systemic risks associated with the availability of critical resources, the integrity of material circulation, and the distribution of their costs and benefits in a socio-ecological system (Singh et al., 2022). The study adopts a combined quantitative and qualitative approach to (a) analyze the WEF-nexus in the Caribbean region with regards to the four dimensions, and to (b) identify and interpret potential socio-metabolic risks associated with WEF-nexus dynamics. The study presented in this Chapter is motivated by the question: Do the trends on these critical resources constitute potential SMRs in Caribbean SIDS? The study presented in this Chapter offers the first attempt at operationalizing the concept of SMRs. It further expands the WEF-nexus literature and aims at providing baseline data for policy and other stakeholders to better understand the resource dynamics, resource availability and security, as well as to properly identify potential barriers and openings for positive transformative change in Caribbean SIDS.

The remainder of this Chapter is organized as follows. Section 3.3 provides a brief review of the origins, evolution, and state-of-the-art research on the WEF-nexus. Section 3.4 outlines the methods, data sources and indicators utilized for analyzing the WEF. In Section 3.5, we present our results in the form of spider-grams for each resource across the four dimensions, followed by a discussion on socio-metabolic risks in section 3.6. Section 3.7 offers a meta-reflection on the key findings of this Chapter.

3.3 State-of-the-art on the Water-Energy-Food (WEF) Nexus

There is no clear consensus on the precise origins of the WEF-nexus concept. Some scholars may argue that it first appeared on *The Limits to Growth* report, stating the "varied but interdependent components-economic, political, natural, and social-that make up the global system in which we all live" (Meadows et al., 1972, p. 9). Similarly, *The Report of the World Commission on Environment and Development* of 1987 stated that sustainable development and natural resources "are connected and cannot be treated in isolation one from another" (Brundtland, 1987, p. 18), suggesting the need of "nexus thinking". Newell et al. (2019) presented a 40-year literature review of WEF-nexus where they highlight academic publications on the (partial) nexus approach from as early as in 1988. A review by Endo et al. (2017) reveals that a large number of nexus-related conferences, initiatives and projects have been held since the early 80's. More prominently, the WEF-nexus concept has gained momentum both in policy and academia in the past decade. Several authors (Albrecht et al., 2018; Biggs et al., 2015; Endo et al., 2017; G. B. Simpson & Jewitt, 2019) agree that one of the key events that marked in earnest the recognition of the WEF-nexus was the Bonn 2011 Nexus Conference *The Water Energy and Food Security Nexus – Solutions for the Green Economy* (Hoff, 2011b). In addition, the 2011 report of the World Economic Forum titled *Water Security – The Water-Food-Energy Climate Nexus* was pivotal in bringing the concept under the global spotlight (The World Economic Forum, 2011). Subsequently, the number of academic publications on the WEF-nexus more than doubled between 2011 and 2016 (Newell et al., 2019).

According to Pahl-Wostl (2017), the focus of WEF-nexus publications in the first 4 years immediately after the Bonn 2011 conference was closely related to resource *security*, and widely promoted in policy and development circles (G. B. Simpson & Jewitt, 2019). In addition, several clusters of research have been identified by Endo et al. (2017) and Newell, Goldstein, and Foster (2019). According to their classification, these clusters range from partial nexuses such as energy-food, energy-biofuels, water-food, and water-energy to a more integrated WEF nexus-based approach, with some clusters exploring even newer concepts such as the urban WEF-nexus or climate-related nexuses. The WEF-nexus concept has also broadened its scope to emphasize the interconnectedness and interdependencies of other resources with the goal to achieve sustainable management of natural resources more generally. The nexus approach has also lent its power to advance conceptual frameworks aimed at understanding problem framing or for promoting cross-sectoral collaboration (Bazilian et al., 2011; de Amorim et al., 2018; Keskinen et al., 2016). Increasingly, the WEF-nexus concept has been mainstreamed in development practice and policy, and also being used at the project planning level with uptake by public and private sectors (FAO, 2018).

The analysis of the WEF-nexus has also covered an umbrella of different tools, scales and approaches to evaluate the nexus (Albrecht et al., 2018). Tools include Integrated Assessment Models (Howells et al., 2013), Material Flow Analysis (Villarroel Walker et al., 2014), Life Cycle Analysis (R. H. Mohtar & Daher, 2014), or Sankey Diagrams (Mukuve & Fenner, 2015), among others. Spatial and temporal scales include Asia-Pacific region (Asian Development Bank, 2013; Taniguchi et al., 2017; UN-ESCAP, 2013), Europe (Magnana et al., 2019), and Latin America and the Caribbean (Mahlknecht et al., 2020), while others have investigated more specific case-studies on the water-energy-food accounting, such as in Egypt (El-gafy, 2017), and Southern Africa (Nhamo et al., 2018). Other groups of scholars have analyzed a partial nexus, or a nexus coupled with emphasis on other aspects such as with ecosystems, land, or climate change (Ferroukhi et al., 2015; Hoff et al., 2013; UNECE, 2015). Yet, only a few studies have adopted the nexus approach to address resource challenges in the island context (see Table 2).

Table 2 - Overview of Water-Energy-Food Nexus studies on island territories across the world

Island territory	Scope of the nexus	Source
Orkney Island (Scotland)	**Water-energy** – Potential for energy generation from tidal power	United Nations Sustainable Water and Energy Solutions Network, (2020)
Mauritius	**Water-energy** – Potential of water desalination through solar energy	United Nations Sustainable Water and Energy Solutions Network, (2020)
Canary Islands	**Water-energy** – Potential of water desalination through solar energy	United Nations Sustainable Water and Energy Solutions Network, (2020)
Mauritius	**Water-energy-food** – Potential of biofuel generation from sugarcane	Giampietro & FAO, (2013).
14 Pacific Island Countries	**Energy-food** – Connections between bioenergy and food security	Chapman, (2009)
Crete, Greece	**Energy-food** – Connections between agriculture and renewable energies	Vourdoubas, (2020)
Small Island Developing States	**Water-food** – Freshwater for food and nutrition security	FAO & Vrije Universiteit Amsterdam, (2020)
St. Eustatius	**Water-energy-food** – Analysis of resource shortages caused by extreme weather events	Daw and Stout, (2019)
Bonaire	**Water-energy-food** – Introductory factsheet of potential nexus interventions	van der Geest and Slijkerman, (2019)
Trinidad & Tobago, Dominican Republic, Jamaica, Haiti, Cuba	**Water-Energy-Food** – Planetary boundaries (including indicators for WEF) within the "safe and just space" framework	Jia, (2019)
Latin America and the Caribbean	**Water-energy-food** – Challenges and opportunities for resource security	Bellfield, (2015)
Latin America and the Caribbean	**Water-energy-food** – Role of green infrastructure in achieving WEF security in the region	IDB, (2019).
The Bahamas	**Water-energy-food** – Options for resource security	Beatty, (2015)
Latin America and the Caribbean	**Water-energy-food** – Baseline and trends of these essential resources in the region	Mahlknecht et al., (2020)
10 Caribbean SIDS	**Water-energy-food** – Evaluation of WEF sustainability under current conditions	Winters et al., (2022)

With respect to the Caribbean, Mahlknecht et al. (2020) performed one of the first WEF-nexus studies, examining the baseline and trends of these essential resources. However, that study was done in combination with Latin America which restricts a fuller understanding of WEF dynamics specifically for Caribbean SIDS. On the other hand, the most complete study to date on the WEF-nexus for

Caribbean SIDS was performed by Winters et al. (2022), in which an evaluation of sustainability under current conditions was performed. However, the approach used in their study provided only a partial view of the WEF-nexus and prevented a more thorough understanding of the resource-use dynamics, particularly the associated risks from such trends. This Chapter attempts to fill this gap by proposing a more comprehensive and meaningful framework for analyzing the WEF-nexus and the implications of these resource-use dynamics from a socio-metabolic risk perspective.

3.4 Methods

Fourteen Caribbean SIDS formed the basis of the analysis of this Chapter's study. The islands analyzed together represent more than 90% of the Caribbean's total population as well as land area, a diversity of landscapes, climatic conditions, island sizes, governance structures, and levels of economic and human development (see Table 3).

Table 3 - Comparative table among countries, showing different biophysical and socio-economic attributes

	Countries	Population 2017	Land area km^2	GDP Per Capita 2017	HDI 2018	Ease of Doing Business Index 2019
1.	**Antigua and Barbuda**	95,400	440	15,820	0.776	113
2.	**Aruba**	105,400	180	25,630	0.908	N/A
3.	**Barbados**	286,200	430	16,300	0.814	128
4.	**Cuba**	11,340,000	103,800	8,540	0.778	N/A
5.	**Dominica**	71,500	750	6,950	0.724	111
6.	**Dominican Republic**	10.510,000	48,300	7,200	0.745	115
7.	**Grenada**	110,900	340	10,200	0.763	146
8.	**Haiti**	10,980,000	27,600	770	0.510	179
9.	**Jamaica**	2,921,000	10,800	5,100	0.726	71
10.	**St.Kitts and Nevis**	52,000	260	19,100	0.777	139
11.	**St. Lucia**	181,000	610	9,600	0.745	93
12.	**St. Vincent and the Grenadines**	110,000	390	7,150	0.738	130
13.	**The Bahamas**	382,000	10,100	31,900	0.805	119
14.	**Trinidad & Tobago**	1,384,000	5,100	16,000	0.799	105

Sources: The World Bank, 2022e, 2022d, 2022b; Villeret, 2022; Worldometer, 2022b. Note: HDI stands for Human Development Index. Ease of doing business was based on a rank among 190 countries.

To evaluate the WEF nexus and operationalize the concept of SMRs for the 14 Caribbean SIDS, key attributes for water, energy, and food are analyzed in two points in time, the years 2000 and 2017. Four resource dimensions were proposed, namely: a) **availability**, b) **access**, c) **consumption,** and d) **self-sufficiency,** which were evaluated and compared with respect to each of the resources. These dimensions are mostly based on the SDGs 2 – Zero Hunger, SDG 6 – Clean Water and Sanitation, and SDG 7 – Affordable and Clean Energy.

- *Availability* is the estimated amount of "exploitable" resources per capita that is potentially available to the population of a country in a given year and that is based on the island's domestic resource-base.
- *Access* is the percentage of the population in a country that can utilize the benefits of a particular resource for their basic needs.
- *Consumption* is the estimated amount of resources consumed per capita each year, and is a measure of affluence.
- *Self-sufficiency* measures the capacity of a country to meet their resource needs through locally available resources.

These four dimensions attempt to encompass most of the characteristics of the dynamics of resource-use in the island context. Availability highlights the abundance or lack thereof of a particular resource. Access and Self-sufficiency build on the physical, social, economic, and political circumstances of the system, and reveals deficiencies and strengths in the supply chain. Consumption describes knowledge and habits of the quality and quantity of the resource consumed: assuming that sufficient resources are available and accessible, the population decides the type of resource to acquire and consume. Additionally, when internal and external pressures are included such as governance or climate change, one could further identify those elements that exacerbate or alleviate SMRs. Figure 2 shows a conceptual figure utilized to operationalize the concept of SMRs.

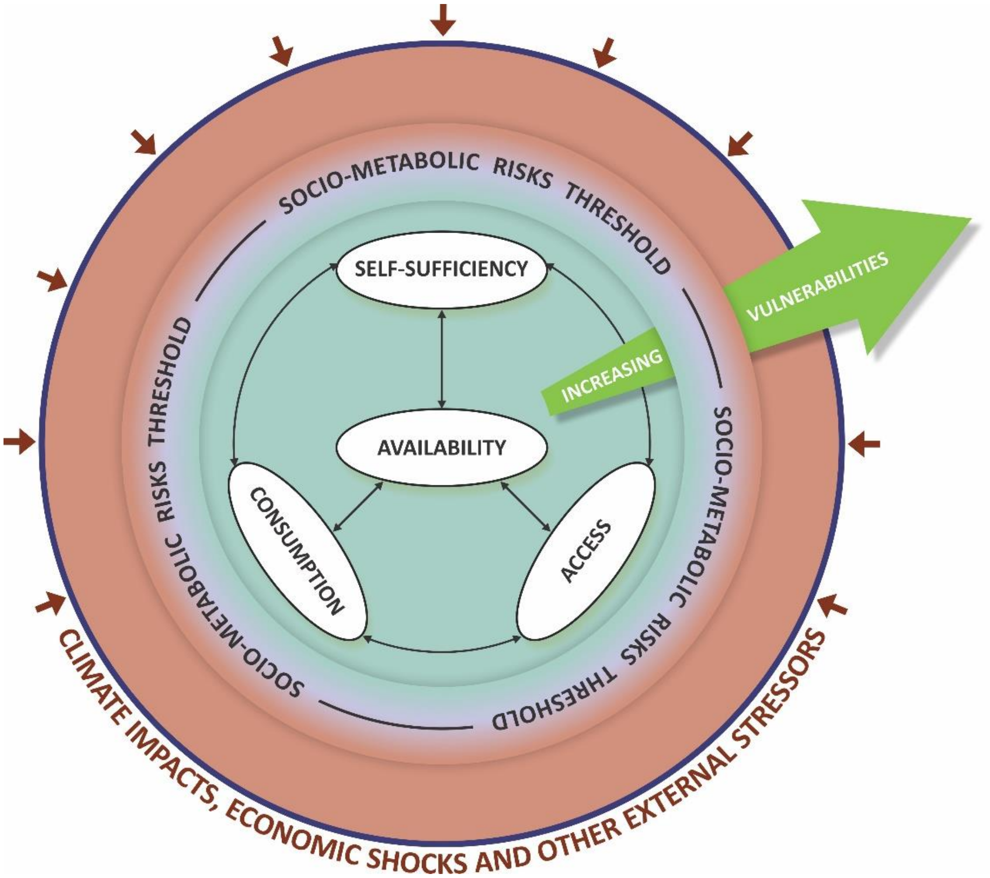

Figure 2 - Conceptual figure utilized to operationalize the concept of socio-metabolic risks (SMRs). Certain combination of resource-use dynamics could entail SMRs, which could lead to weak coping and adaptive capacities to face systemic risks. At the same time, a better understanding of these resource-use dynamics and SMRs could enhance resource performance across all the dimensions through identifying potential barriers and openings for positive transformative change.

Results are visualized using spider-grams, a technique that enables the identification of the different variations in performance of all resources involved with respect to a specific dimension. To aid comparison, the performance on resource **access** and **self-sufficiency** was measured both in percentages (from 0% to 100%). For resource **availability** and **consumption,** the performance was visualized through a single range scale going from zero to the maximum estimated value between the two years analyzed**.** Average numbers for the 14 case studies analyzed are also included in the spider-grams for each dimension. Table 4 below provides further details on data sources, description and calculations for the analysis of this Chapter’s study. The Appendix A provides underlying data in tabular form for all figures in Chapter 3.

Table 4 - Description, calculations, and sources of the different dimensions utilized to analyze the Water, Energy, and Food

	Dimensions	Description	Calculations	Sources
WATER	**Availability** [m^3/cap/yr]	Amount of “exploitable” water per capita that is potentially available to the population	(Total Renewable Surface Water plus Total Renewable Ground Water) divided by population	(FAO, 2022b; The World Bank, 2022k)
	Access [**%**]	Average percentage of the population having basic drinking water and sanitation services	Directly obtained from source	(FAO, 2022b)
	Consumption [m^3/cap/yr]	Amount of consumed water per capita per year	(Fresh water withdrawals plus desalinized water) divided by population	(FAO, 2022b)
	Self-sufficiency [%]	Share percentage of total water consumed that is domestically harvested, or from within the national boundary	100% minus Water Dependency Ratio measured in percentage	(FAO, 2022b)
ENERGY	**Availability** [GJ/cap/yr]	Amount of primary energy per capita that is potentially available to the population	(Non-renewable energy plus renewable energy) divided by population	(CARICOM, 2018b; EIA, 2022a; Energypedia, 2022; Herbert, 2013; IRENA, 2012a; NREL, 2015e; Ochs et al., 2015)
	Access [**%**]	Share percentage of population in each country that have relatively simple, stable access to electricity	Directly obtained from source	(The World Bank, 2022a)
	Consumption [GJ/cap/yr]	Amount of consumed energy per capita per year	Total primary energy consumption divided by population	(EIA, 2022a)
	Self-sufficiency [**%**]	Share of total energy consumption satisfied from locally extracted primary energy resources	Directly obtained from source	(EIA, 2022a)
FOOD	**Availability** [kg/cap/yr]	Amount of available food per capita	Directly obtained from source	(FAO, 2021a)
	Access [%]	Proportion of the population at or above the minimum level of dietary energy consumption based on the 3-year average prevalence of undernourishment.	100% minus prevalence of undernourishment measured in percentage	(FAO, 2022a; FAO et al., 2015)
	Consumption [kcal/cap/day]	Refers to the quantities of food available for human consumption at the retail level by the country’s resident population (apparent consumption)	Directly obtained from source	(FAO, 2021a)
	Self-sufficiency [%]	Share of food coming exclusively from local production	Total food availability divided by total locally produced food	(FAO, 2021a)

3.4.1 Features considered for the WEF-Nexus and the operationalization of socio-metabolic risks

The analysis of this Chapter relied primarily on international data sources like FAO AQUASTAT database for water, FAO Food Balance Sheets database for food, and a variety of international platforms and institutions that compile information on the energy sector such as the U.S. Energy Information

Administration, IRENA, NREL, and others. Where possible, national statistics were consulted to complement this Chapter's results. Due to data constraints and compilation methodologies, we only included the years 2000 and 2017 in this analysis. Section 6.4.1 provides further details on datasets limitations.

Water – For water availability, all available internal renewable water resources (surface water and ground water) was accounted for. Water that was desalinized for utilization of the island was not considered, as this is drawn from outside the island's boundary (therefore an "import") and is not regulated by the island's internal hydrology. For water access, "basic sanitation" refers to facilities that are not shared with other households and include flush/pour flush toilets connected to piped sewer systems, septic tanks or pit latrines, or pit latrines with slabs (including ventilated pit latrines), or composting toilets (The World Bank, 2022e). "Basic drinking water" refers to "water coming from an improved source, provided collection time is not more than 30 minutes for a round trip. Improved water sources include piped water, boreholes, or tube-wells, protected dug wells, protected springs, and packaged or delivered water" (ibid).

Energy - For energy availability, fossil fuel reserves (oil and natural gas), and potentials of renewable energy were accounted for. Energy sources for total primary energy consumption include coal, natural gas, petroleum and other liquids, and nuclear. Renewable energy potentials include wind, solar, hydro, biomass, and geothermal energy. Energy access refers to the percentage of population in each country that have relatively simple, stable access to electricity and related services. It can also be seen as the "electrification rate". Energy self-sufficiency accounts only for locally extracted primary energy resources (fossil, biomass), as well as for installed capacity of renewable energy generation.

Food – Food availability accounts for all food (inclusive of primary crop harvest, marine catch, main livestock products and processed foodstuff) reaching the consumer at households and outside home (e.g., restaurants, etc.) for residents only. Residents include refugees and long-term guest workers and exclude tourists or temporary visitors. This dimension corresponds to the "Food Supply Quantity" indicator from FAO – Food Balance Sheets and is essentially the food available for consumption measured in kg/cap/yr. The "Prevalence of undernourishment" was utilized to account for Food Access. It expresses the probability that an individual consumes an insufficient amount of daily calories for an active and healthy life and it is an indicator of lack of food access. Food consumption refers to the estimated energy content from foodstuffs available for consumption, measured in caloric value (kcal/cap/day). This indicator can be useful to determine if the food availability is of sufficient energy content to meet the resident's needs. Food self-sufficiency accounts for the country's capacity to meet its own food needs from domestic food production.

3.5 Results

On average, the availability of locally exploitable resources for the case studies analyzed showed a decreasing trend between 2000 and 2017. Simultaneously, there is not only an increase in the universal access of WEF by island citizens but growing affluence and industrial development has also led to higher levels of resource consumption and lower self-sufficiency, especially for energy (at 14%) and food (at 70%). Water consumption and primary energy consumption both increased 20%, while food consumption slightly increased 5%.

3.5.1 Water performance

Between 2000 and 2017, the Caribbean SIDS did not show a significant change in the available (or potentially exploitable) water resources per capita as it went from 1,900 m^3/cap/yr to 1,700 m^3/cap/yr. Water access showed small improvements in the region, going from 83% to 89%. Water consumption per capita slightly increased from 230 m^3/cap/yr to 275 m^3/cap/yr. There was no change in the region's water self-sufficiency levels, staying at 90%. The results of our methodology are comparable with the results of the WEF study in Caribbean SIDS presented by (Winters et al., 2022) for water availability, access, and consumption. Nonetheless, slight variations remain due to completeness of the data, indicator definitions, and differences in data compilation methodologies. Figure 3 shows the water spider-grams of the 14 Caribbean SIDS across all four dimensions during the years 2000 and 2017.

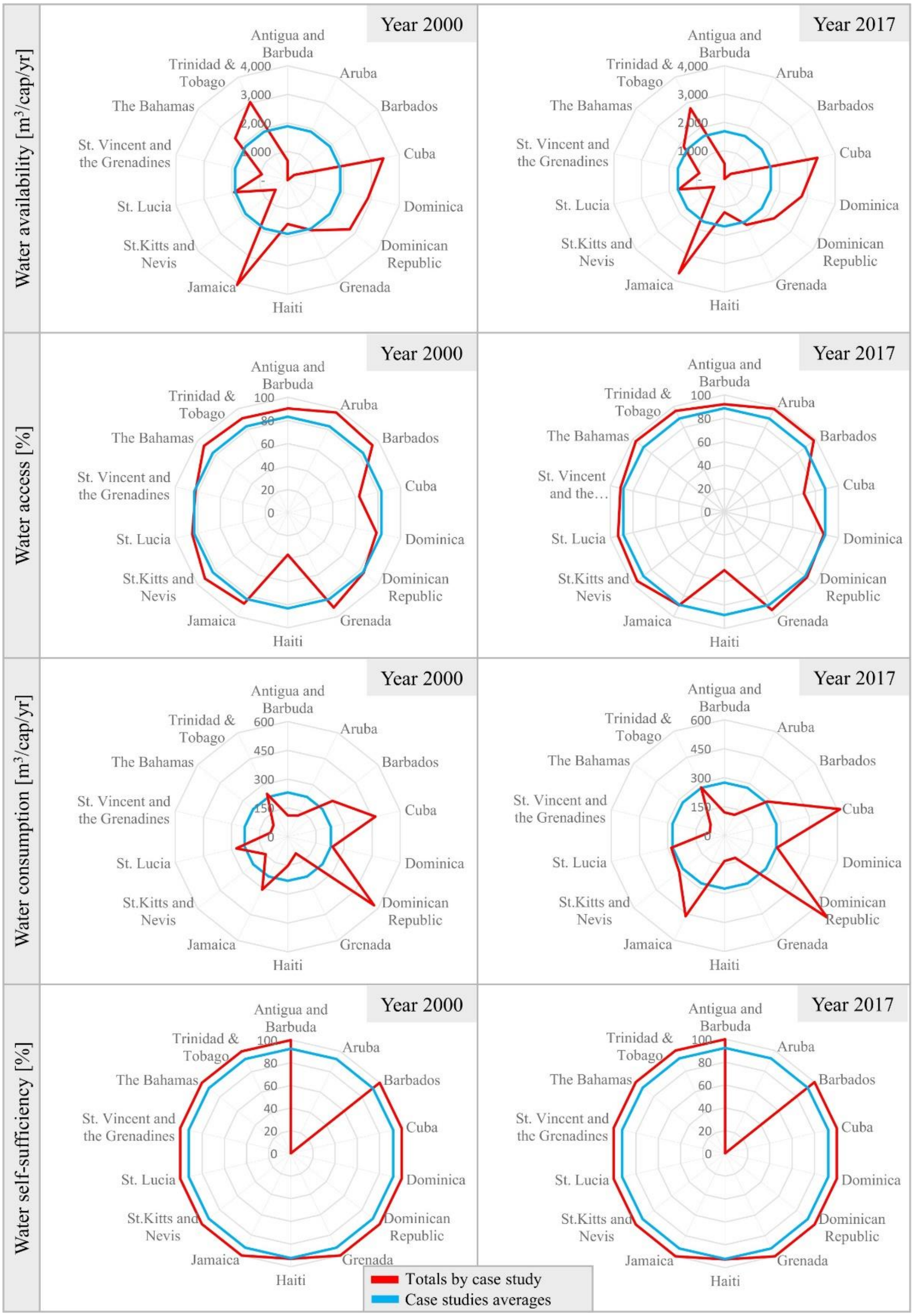

Figure 3 - Caribbean SIDS water spider-gram for the years 2000 and 2017.

For availability, Antigua and Barbuda, Barbados, and St. Kitts and Nevis show values of less than 700 m^3/cap/yr for both 2000 and 2017, with Aruba having values close to 0 m^3. In comparison, other countries show more than four times this water availability. Jamaica in 2000 exhibits water resources of around 4,000 m^3/cap/yr, followed closely by Cuba and Trinidad & Tobago, with values of around 3,400 and 3,000 m^3/cap/yr respectively. In 2017, Jamaica and Trinidad & Tobago reduced their availability by around 9%, moving to 3,700 m^3/cap/yr and 2,800 m^3/cap/yr respectively.

Water access increased from 83% in 2000, to 89% in 2017. Improvements in water access was seen across all countries. Haiti and Cuba, which have the lowest access scores in the region, increased their water access from 36% to 50% for Haiti, and from 63% to 70% for Cuba.

Water consumption per capita for Caribbean SIDS in the year 2000 was close to 230 m^3/cap/yr, increasing 20% in 2017 to 275 m^3/cap/yr, showing an overall rising trend of total water use. The highest water consumptions per capita for Caribbean SIDS were for Cuba and Dominican Republic, with 470 and 570 m^3/cap/yr respectively in 2000. Consumption increased by 30% for Cuba (to 610 m^3/cap/yr) and by 20% for Dominican Republic (to 680 m^3/cap/yr) in 2017. St. Vincent and the Grenadines, and The Bahamas present the lowest values for both periods, with 93 and 94 m^3/cap/yr respectively for the year 2000, and 77 and 92 m^3/cap/yr respectively for the year 2017.

On average, no change was found in the region's water self-sufficiency. Most countries are 100% water self-sufficient, except for Haiti, which has around 90% water self-sufficiency, and Aruba with values close to 0%. Aruba lacks enough surface water and ground water to satisfy their needs. This country partially overcomes that challenge through desalination of sea water.

3.5.2 Energy performance

Between 2000 and 2017, Caribbean SIDS remained constant in the average availability of energy resources (210 GJ/cap/yr in 2000 and 160 GJ/cap/yr in 2017), however there are great disparities between countries as changes mainly depend on fossil fuel reserves. Significant improvements in energy access in the region took place, advancing from 85% to 96%. Average energy consumption per capita increased from 89 GJ/cap/yr to 110 GJ/cap/yr. Overall, energy self-sufficiency in the region remains low at only 14%. This Chapter's results are in a similar range when cross-checked with independent studies that include an analysis on energy access and energy self-sufficiency in Caribbean SIDS (OECD et al., 2021; Surroop et al., 2018). Figure 4 shows the energy spider-grams of the 14 Caribbean SIDS across all four dimensions during the years 2000 and 2017.

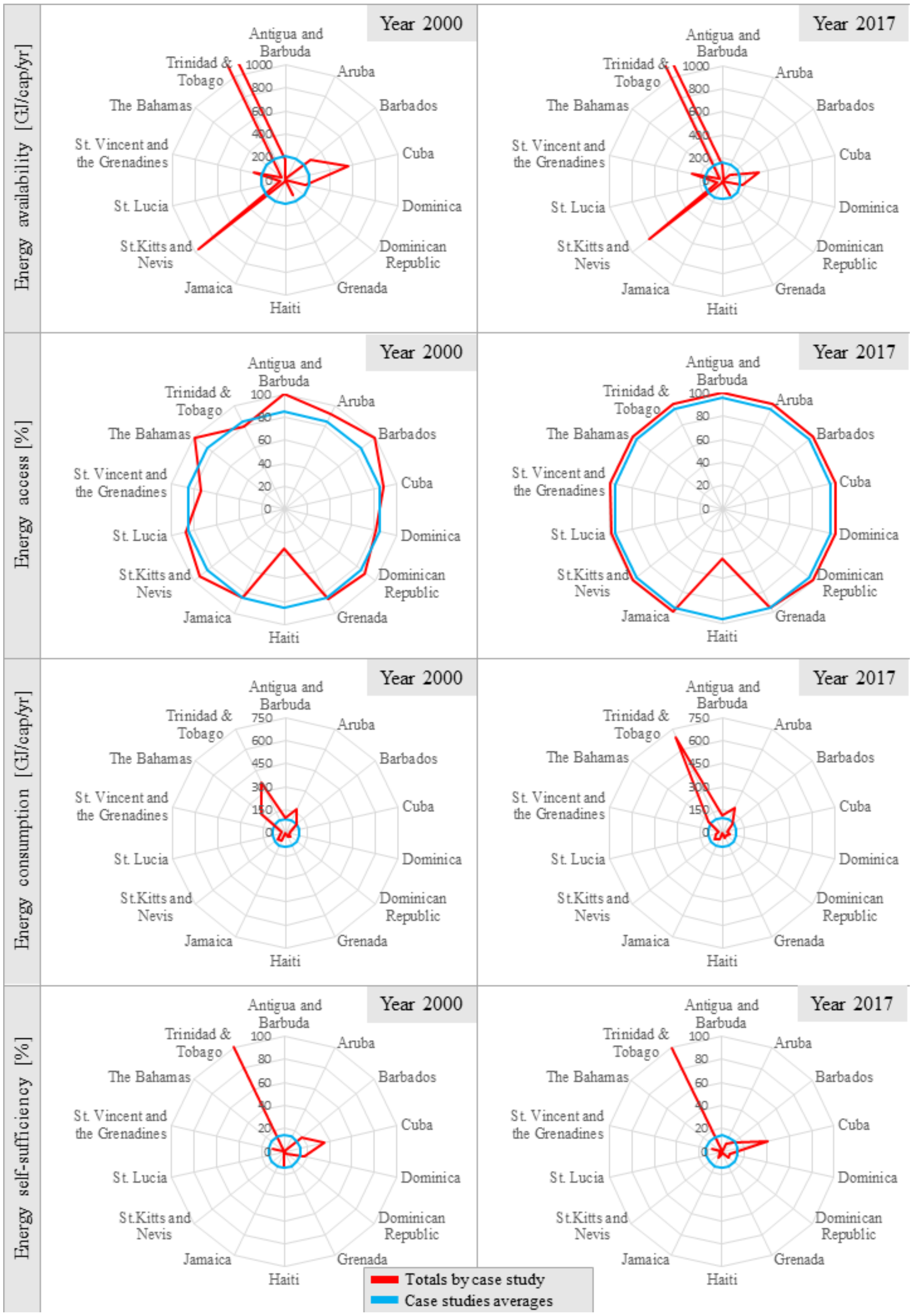

Figure 4 - Caribbean SIDS energy spider-gram for the years 2000 and 2017. As Trinidad & Tobago exhibits a contrasting difference as compared to the rest of Caribbean SIDS for energy availability, a maximum "boundary" of 1,000 GJ/cap/yr was set so the rest of the countries could be better visualized

Throughout the region, huge disparities among individual countries were found in terms of energy availability. The only 3 countries in analyzed in this Chapter with proven fossil fuel reserves are Trinidad & Tobago, Barbados, and Cuba (EIA, 2022b). In 2017, the countries that continue having fossil fuel reserves are Trinidad & Tobago and Cuba, however the reserves from Barbados significantly diminished (EIA, 2022d). The country with the highest renewable energy potential is St. Kitts and Nevis, followed by St. Vincent and the Grenadines, Dominica, and Antigua and Barbuda. This renewable potential comes mainly from geothermal energy (for St. Kitts and Nevis, Dominica, and St. Vincent and the Grenadines), and Wind (for Antigua and Barbuda) (CARICOM, 2018a; Herbert, 2013; IRENA, 2012b; NREL, 2015a, 2015b, 2015c, 2015f, 2015h, 2015g, 2015i, 2020; Ochs et al., 2015).

Trinidad & Tobago's available energy per capita (mainly from fossil fuels) is the highest from Caribbean SIDS for both years, with a value of around 34,000 GJ/cap/yr in 2000 and around 13,000 GJ/cap/yr in 2017. The country with the second highest availability is St. Kitts and Nevis with 960 GJ/cap/yr and 810 GJ/cap/yr for 2000 and 2017 respectively. Cuba ranks third with 560 GJ/cap/yr in 2000, and 320 GJ/cap/yr in 2017.

Without accounting for Trinidad & Tobago, the average value of energy availability per capita in the year 2000 was 210 GJ/Cap/yr, while in the year 2017 was of 160 GJ/cap/yr. The lowest values of exploitable energy are for Dominican Republic and Haiti with less than 5 GJ/cap/yr for both years. In 2000 and 2017, the exploitable energy potential for 6 out of 14 countries was below 50 GJ/cap/yr. Barbados dropped 70% from 280 GJ/cap/yr to around 80 GJ/cap/yr. The remaining countries were over 130 GJ/cap/yr in both years.

Energy access for the year 2000 was 85% on average, and increasing to 96% in 2017. Antigua & Barbuda, Barbados and The Bahamas showed 100% energy access for both years, while countries such as St. Vincent and the Grenadines, Trinidad & Tobago, and Dominica show a 26%, 20%, and 19% increase in energy access respectively between the years 2000 and 2017. In the year 2017, Aruba, Cuba, Dominica, Dominican Republic, Jamaica, St. Kitts and Nevis, St. Vincent and the Grenadines, and Trinidad & Tobago reached 100% energy access. Haiti's score was the lowest for both years, with 34% and 44% for the years 2000 and 2017 respectively, with huge variation in access between rural and urban populations.

Among Caribbean SIDS, Trinidad & Tobago has the highest energy consumption per capita for both years, almost doubling from 370 GJ/cap/yr to 690 GJ/cap/yr in 2000 and 2017 respectively, which is more than 4 times the regional average of 89 GJ/cap/yr in 2000 and 110 GJ/cap/yr in 2017. The Bahamas and Aruba ranked second (200 GJ/cap/yr) and third (180 GJ/cap/yr) in 2000. The rest of the countries were below the 100 GJ/cap/yr in both years. Noticeably, Haiti exhibits consumptions of less than 5 GJ/cap/yr for both years.

On an average, no change in the region's energy self-sufficiency, remaining low at only 14%. Trinidad & Tobago was the only country with 100% energy self-sufficiency during both years. Cuba ranks second, at 35% in 2000 and increasing to 41% in 2017. The rest of the countries fall below the 20% of energy self-sufficiency for both years. Antigua & Barbuda, Aruba, Grenada, St- Kitts and Nevis, St. Lucia, and The Bahamas had 0% self-sufficiency in 2000, and virtually no progress was made up to 2017. The most effort in self-sufficiency was seen on Aruba, which increased from 0% in 2000 to 8% in 2017.

3.5.3 Food performance

Average food availability remained constant at around 654 kg/cap/yr, but with high variations between countries. Considerable improvements in sufficient food access were observed, increasing from 81% in 2000 to 88% in 2017. Moderate change in food consumption per capita was observed as consumption changed from 2,570 kcal/cap/day in 2000 to 2,700 kcal/cap/day in 2017. Overall, food self-sufficiency dropped from 78% in 2000 to 67% in 2017. For food availability and self-sufficiency, the results of our methodology during 2000 and 2017 are in line with the results of the study on biomass flows accounting performed by Rahman et al. (2022) when considering primary crop harvest, marine catch, and main livestock products. A study by the Caribbean Public Health Agency (2017) on food consumption (in kcal/cap/day) in the Caribbean also validates our findings. Figure 5 shows the food spider-grams of the 14 Caribbean SIDS across all four dimensions during the years 2000 and 2017. Food statistics for Aruba were unavailable and have been left out of the visualizations. Nonetheless, a report from The World Bank highlights that food self-sufficiency in Aruba is extremely low, whereas food availability and access are high (Boyer et al., 2020).

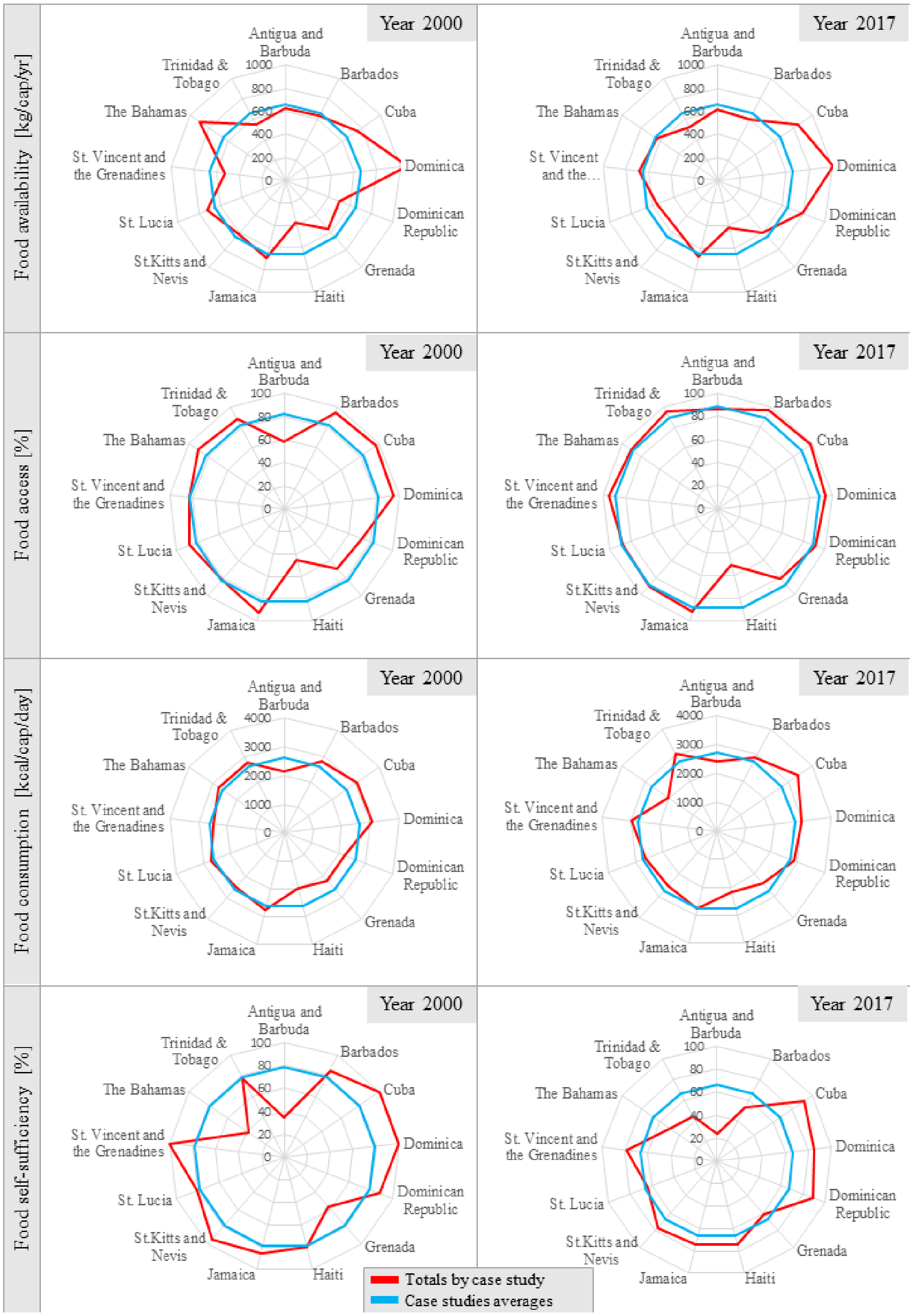

Figure 5 - Caribbean SIDS food spider-gram for the years 2000 and 2017.

Slight differences among individual countries in terms of food availability could be observed. Dominica showed the highest levels at above 1,000 kg/cap/yr during both years, while Haiti showed the lowest levels at 380 kg/cap/yr and 420 kg/cap/yr for 2000 and 2017 respectively. Dominican Republic had a drastic increase in food availability (close to 60%) going from 500 kg/cap/yr to 790 kg/cap/yr. Contrastingly, The Bahamas dropped significantly (close to 30%), from 900 kg/cap/yr to 640 kg/cap/yr. A decline in food availability of almost 30% was also observed in St. Lucia, going from 720 kg/cap/yr to 560 kg/cap/yr.

Reported sufficient food access of more than 80% was seen in 9 out of 13 countries in 2000, while for 2017 these increased to 12 out of 13 countries (no data was available for Aruba). The countries with the highest access were Barbados, Cuba, and Dominica with values above 94% in both years. The country that showed the highest increase in food access was Antigua and Barbuda, with 58% in 2000, and that increased to 86% in 2017. For both years, Haiti had the lowest food access, with 45% and 51% in 2000 and 2017 respectively.

In 2000, the highest food consumption per capita was seen in Cuba and Dominica, both at around 3,000 kcal/cap/day. In the same year, Haiti had the lowest score, with around 2,000 kcal/cap/day that increased 10% to 2,200 kcal/cap/day in 2017. In 2017, Cuba overtook Dominica as the highest food consumer with 3,400 kcal/cap/day, followed closely by Trinidad & Tobago, St. Vincent and the Grenadines, and Dominica at around 3,000 kcal/cap/day. Between 2000 and 2017, nine countries had an increasing trend in their food consumption per capita, with the maximum increase being for Dominican Republic (30% more), from 2,200 to 2,900 kcal/cap/day. On the other hand, The Bahamas showed the highest decline in their consumption per capita in the same period (35% less), going from 2,800 to 2,000 kcal/cap/day.

Food self-sufficiency in the region showed a steep decline between 2000 and 2017, from 78% to 67%, also with significant variations between countries. Cuba and St. Vincent and the Grenadines have the highest self-sufficiency ratio in the region in both years, at 100%. Countries with the lowest self-sufficiency in 2000 were Antigua and Barbuda and The Bahamas, both at levels below 40%. The rest of the countries are above the 50% self-sufficiency ratio. In 2017, the food self-sufficiency ratio for Antigua and Barbuda declined to 23%, followed by St. Kitts and Nevis at 77%. The rest of the countries were all above 50% food self-sufficiency. The country with the highest increase in self-sufficiency was The Bahamas, going from 37% in 2000 to 50% in 2017. The countries that showed the highest decrease in self-sufficiency were Trinidad & Tobago (from 78% to 44%), Barbados (from 85% to 53%), and St. Vincent and the Grenadines (from 100% to 78%).

3.6 Do the trends in WEF in the Caribbean SIDS demonstrate socio-metabolic risks?

Singh et al. (2022, p. 7) define SMRs 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 this sense, specific resource dynamics can entail SMRs and cascade effects, which in turn inhibit progress towards greater resource security, self-reliance, and the system’s ability to continue delivering societal services necessary for survival (ibid). In the island context, their distinct characteristics of economic model, small size, remoteness, biogeography, limited resource-bases and more, could present a scenario where SMRs can occur. From the analysis of this Chapter, one can observe that Caribbean SIDS exhibit distinct WEF dynamics conductive of varying degrees of SMRs.

In the following sub-sections, each resource and potential SMRs at the level of the region is discussed. However, one needs to consider variations, shifting baselines, and context when it comes to country-level planning. Table 5 offers an overview of the observed SMRs for each resource and across all four dimensions analyzed.

Table 5 - Overview of some associated water, energy, and food SMRs with respect to the dimensions of Availability, Access, Consumption, and Self-sufficiency in Caribbean SIDS

	Associated SMRs			
Dimension	**Availability**	**Access**	**Consumption**	**Self-sufficiency**
WATER	Declining levels of water availability: • water shortages • lower recharge capacity through changes in hydrology • water stocks contamination through saline water intrusion and other pollutants	Unequal access between social groups: • water insecurity • social unrest • decline in local food production • increased household and government expenditures	Quantity and quality of the resource is compromised: • exhaustion of water stocks • political and socio-economic instability • ecosystems damage • impacts on human health	Demand larger than supply: • water scarcity and water crisis • impacts on local economy • decline in local food production
ENERGY	Damages during transport and extreme weather events: • oil spills and runoffs • shortages due to disruption on supply • degradation of marine and coastal ecosystems • impact on local development and economy	Frequent energy provisioning disruptions: • quality and stability of the supply (blackouts) • impacts on health, agriculture, drinking water, sanitation, and food • increased energy consumption	Deficiencies of affordable and clean energy supply: • increased consumption • transmission and distribution losses • elevated energy tariffs • pressure on grid and risk of destabilizing it • impacts on health and national energy security	Fossil-fuel dependent economies: • imports dependency is perpetuated • increased exposure to external shocks • delays in recovery responses in case of disasters
FOOD	Low resource productivity and competing land uses: • decline in arable land (less than 0.06 ha/cap) • decline in locally sourced food (less than 20%) • increased import dependency and food bills	Deficiencies in food security: • prevalence of undernourishment • impairing of human development • intergenerational cycle of malnutrition and poverty	Shift from healthier diets to nutritionally inferior diets: • higher levels of non-communicable diseases such as stunting, wasting or anemia • low work productivity • poor school performance • loss of healthy life	Deficiencies in the agri-food supply chain: • decline in domestic foodstuff production • higher food losses • increased food insecurity • increased foodborne hazards and diseases outbreaks

3.6.1 Water and socio-metabolic risks

Water resources in Caribbean SIDS are limited as these exhibit special vulnerabilities to anthropogenic and natural pressures. From our case studies analyzed, 5 Caribbean SIDS are already below the thresholds of water stress levels of 1,000 m^3/cap/yr established by the UN-Water organization (UN-Water TF-IMR, 2009), while 10 are at risk of medium water scarcity, and 4 at very high risk of water scarcity, especially for low-lying islands such as Barbados and The Bahamas (UNESCO-IHP & UNEP, 2017). For Caribbean SIDS, the risk of water scarcity and water crisis increases as demand steadily becomes larger than supply (Holding et al., 2016) (see Table 5, Water Access and Self-sufficiency). The concentration of population and industries in dense urban areas and the growing tourism develops into higher water demand and in changes in surface water and groundwater quality. This increasing risk is partially caused by the conversion of catchment areas for urban development zones or for agriculture, by fresh-saline water interface migration, chemical pollution, and improper sewage disposal, among others. Moreover, during natural hazards, the already limited freshwater resources are often contaminated by seawater, and pollutants intrusion, which in turn further jeopardize water security and health (Dubrie et al., 2022; UNESCO & UN-Water, 2020; UNESCO-IHP & UNEP, 2017) (see Table 5, Water Availability and Consumption). We can already observe evidence of this in Jamaica, Trinidad & Tobago; Antigua and Barbuda, Barbados, and Aruba (Cashman, 2014; Kelman & West, 2009).

The impacts of climate change can have severe consequences in resource security, especially with projections of 2 degrees Celsius warming above preindustrial levels by 2030 (Drakes et al., 2020; Karnauskas et al., 2018). Large variability of rainwater and temperature has been observed in Caribbean SIDS: a rise in temperature exceeding 0.5°C has been registered since 1900 (Nurse et al., 2001) and projections in total annual rainfall by 2100 relative to 1961–1990 range from -50 to +30% (Mimura et al., 2007). This situation is conducive of a major shift in frequency and intensity of extreme weather events such as droughts and heat waves which, combined with sea-level rise, will also cause higher incidences of flooding in coastal zones of SIDS, with increased saltwater intrusion into surface and groundwater aquifers (Lincoln, 2017) (see Table 5, Water Availability). Being in a situation of water scarcity could then exacerbate inequalities within countries, especially for the poorest populations (e.g., Dominican Republic, Haiti, St. Lucia)(WHO & UNICEF, 2021). Insufficient access to clean water resources increases people's vulnerabilities, which in turn contributes to health problems and lower employment rates, as well as social unrest, and increased household and government expenditures, among others (ECLAC, 2022; UN, 2021) (see Table 5, Water Access).

Droughts caused by declines in precipitation during the wet season are likely to increase in frequency and severity by the end of the 21st century (IPCC, 2015). The harsh 2009-2010 and 2014-2016 Caribbean-wide drought events resulted in significant impacts across multiple sectors, including decline of hydropower generation, reduction of crop yields, increases in food prices, riots, increase in diseases proliferation, livestock losses and human fatalities (Cashman, 2014; EM-DAT & CRED, 2022; Trotman et al., 2021). Derived from this, progress has been made among Caribbean SIDS to adapt desalination technologies as a source of supply in preparation for future water scarcity. Aruba is almost 100% reliant on this technology to satisfy the water demand, while the installed capacity for Antigua and Barbuda reaches almost 60% of its total demand. Nonetheless, desalination is characterized as having high operation and maintenance costs which oftentimes is affected by disruptions in the supply chain as these depend from a great deal of (usually imported) energy for its operation (UN, 2018a). Resource allocation to ensure sufficient levels of clean water and sanitation among the population should be prioritized, thus care should be taken as plans have to accommodate for the current and future resource-bases of the territory (UNWTO, 2014).

Overall, there are some SMRs that were identified during this analysis: vulnerability to water shortages and extreme weather events, ecosystem degradation, threats to local food production and access inequality, among others. Solutions to mitigate these will require actions aligned to SDG 6 and that encompasses strategies that strengthen the reliability and availability of water supplies needed to meet economic, environmental, and social development (e.g., waste management practices to ensure the protection of water quality, wastewater reuse and recycling, or incentives for eco-friendly practices). This in turn will also aid in human health and wellness, food production, energy generation, manufacturing of goods, as well as sustained biodiversity (IWRA, 2023; Nagabhatla et al., 2019).

3.6.2 Energy and socio-metabolic risks

With a very limited renewable energy generation capacity, the energy resource-base of Caribbean SIDS is largely dependent on fossil fuels for over 80% of their primary energy supply (ECLAC, 2016; UNESCO, 2017). Available fossil fuel reserves for Trinidad & Tobago, Barbados, and Cuba are declining due to accelerated exploitation, especially for Barbados (EIA, 2022d). Investments in new oil exploration zones (e.g. on and offshore the coasts of The Bahamas, Jamaica and Dominican Republic) have not yielded positive results as fossil fuel sources were not quantifiable or easily accessible (Geo ExPro, 2019; Vyawahare, 2021). The distribution of fossil fuels within the region is managed through large vessels passing between the islands, oftentimes resulting in high risks for oil and chemical spills that threaten the entire Caribbean ecosystem, in addition to the threat of a decrease in tourism due to closure of recreational areas. Major oil spills and beach pollution have already been reported in major tourist destinations such as Trinidad & Tobago, The Bahamas, Barbados, Grenada, Dominica, and St. Lucia, among others (Save the Bays & Waterkeeper Alliance, 2019; UNEP, 2022). The negative effects of these harmful chemicals are diverse, however one of the most concerning ones is the impact on marine and coastal ecosystems, potentially causing genetic mutations that could endanger species reproduction and the ability to maintain healthy ecosystems, thus leading to long-term ecosystem collapse (Degnarain, 2020) (see Table 5, Energy Availability). Moreover, the utilization of cleaner energy sources for cooking and heating is still deficient for Caribbean SIDS, with close to 20% of the population still utilizing traditionally low-efficient technologies and lower quality fuels like biomass from agricultural products, charcoal, dung, and fuelwood (WHO, 2022b) (see Table 5, Energy

Consumption). This situation leads to high levels of household and ambient air pollution, with mortality rates per 100,000 inhabitants of 180 in Haiti compared to 20 in The Bahamas, and 39 in LAC (The World Bank, 2022g).

Overall, the energy sector plays a critical role in the provisioning of essential services as these require energy for everyday activities, including recovery in case of disasters. Energy provisioning systems, including those of buildings, infrastructures, and machinery, are key to transform flows of energy and materials into useful services. Among Caribbean SIDS, these systems vary between countries and are oftentimes subject to the negative impacts of climate change. Coupled with their socio-economic and physical exposure to disasters, future affectations on infrastructure, disruptions in supply and changes in consumption present an existential threat that may lead to dangerous and unpredictable SMRs and potentially to system collapse (Singh et al., 2022; UNISDR, 2015). When disasters strike, the quality and stability of the electrical supply is also affected, impacting households and industries in general (e.g. electrical outages), thus, shocking most socio-economic sectors and delaying recovery responses (Erlick, 2021; Flores & Peralta, 2019) (see Table 5, Energy Consumption and Self-sufficiency). The passage of Hurricane Matthew in 2016, and Irma and Maria in 2017 caused extensive damages to critical infrastructure, including the electrical power sector. The interruption of the electricity supply heavily impacted on water and food security, as well as on other essential sectors across the Caribbean SIDS (ACTED, 2016; BBC News, 2017; OCHA & UNCT-Cuba, 2016; UN, 2018b; UNDP, 2017). In The Bahamas, Matthew damaged close to 50% of the electrical power sector, causing electrical outages that lasted for more than one week, and that affected more than 100,000 consumers and impacting over the availability of drinking water, sanitation, food, and health (ECLAC, 2020).

Evidence suggests that Caribbean SIDS have embraced an energy strategy still dependent on fossil fuels that could quickly lead to severe metabolic risks and cascading effects and become a metabolic trap. Trends in energy consumption in Caribbean SIDS are above the world's average (EIA, 2022d), partially attributable to changes in the standards of living and also to large energy system losses (see Table 5, Energy Access, Consumption, and Self-sufficiency). Estimated average electricity transmission and distribution losses for the selected Caribbean SIDS case studies are at around 30% (IDB, 2013; NREL, 2015b, 2015c, 2015f, 2015h, 2015g, 2015i, 2015j, 2020), with countries such as Haiti, St. Kitts and Nevis, and St. Vincent and the Grenadines reaching more than 60% in losses (IDB, 2013; NREL, 2015b). By comparison, the U.S. Energy Information Administration reports average transmission and distribution losses of 5% for the United States (EIA, 2022c). Moreover, Caribbean

SIDS have electricity tariffs higher than the world average of US$0.14/kWh (J. Smith, 2020). Prices range from US$0.44/kWh for Grenada (NREL, 2015h) and US$0.39/kWh for Antigua & Barbuda (NREL, 2015j) and Haiti (NREL, 2015b), to US$0.26/kWh for Dominican Republic (Escalante, 2019) and US$0.04/kWh for Trinidad & Tobago (NREL, 2015d). As electricity tariffs rates increase, so are the access inequalities among the population. Energy theft through illegal connections to the grid could then ensue, which are currently one of the main causes of non-technical electricity system losses in Caribbean SIDS (ECLAC, 2016; Ochs et al., 2015). A feedback-loop could be created as energy theft imposes elevated costs to ratepayers and in turn increases electricity tariffs (see Table 5, Energy Access). The high fossil fuels dependency, large energy losses due to theft, increasing consumption patterns, threats to supply disruptions and fossil fuel price volatility put at risk the national energy security and other critical sectors in many Caribbean SIDS.

Coupled with a limited domestic energy generation capacity, elevated and growing rates of energy consumption, and high electricity tariffs, several Caribbean SIDS also experience an unstable supply of energy with recurrent power outages, further threatening energy security (see Table 5, Energy Access). According to the System Average Interruption Duration Index (SAIDI), power outages in Caribbean SIDS reach above 7 hours/year, which place them at levels above the global average of 3 hours/year (The World Bank, 2022d; WEB Aruba, 2022). The interruption of the energy supply can negatively impact telecommunications, water supply and sanitation, food security, health, and household expenditures, among others (Hull-Jackson & Adesiyun, 2019; Jimenez et al., 2016; Mcintosh, 2020; Weiss et al., 2021). As future power outages are certain to recur, fuel supply disruptions are also a permanent feature, and the adverse effects of climate change will likely amplify pre-existing vulnerability levels in the region (see Table 5, Energy Availability, Access, Consumption, and Self-sufficiency). 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. Moreover, considering the plentiful renewable resources that Caribbean SIDS could exploit (CARICOM, 2018a; Herbert, 2013; IRENA, 2012b; NREL, 2015a, 2015b, 2015c, 2015f, 2015h, 2015g, 2015i, 2020; Ochs et al., 2015), the diversification of the energy mix offers an opportunity to mitigate metabolic risks by reducing price volatility and the potential for supply disruptions, resulting in more energy self-sufficiency and in a resilient and stable energy supply in the long run. In addition, if Caribbean SIDS become energy self-sufficient, then surplus clean energy could also assist nearby island nations in meeting their renewable energy targets. Nonetheless, financial, infrastructural and organizational challenges hinder progress to achieve such transition (ECLAC, 2015; Harrison & Popke, 2018).

The deployment of affordable and clean energy (Aligned to SDG 7) is considered an effective tool to raise productivity and competitiveness, energy security, energy access, and self-sufficiency, and to address the negative SMRs of the high-dependence of fossil fuels (e.g., impacts on local health, degradation of ecosystems) in an integrated way. Benefits are also achieved through increased diversification of the power supply (e.g., ocean-based energy generation) and improved energy access, which lowers the risk of a single resource having an adverse impact on the national energy security (OHRLLS, 2019). Moreover, synergistic effects can be achieved through the utilization of clean energy for water desalination technologies, thus, reducing the associated costs of operation and maintenance while at the same time increasing water supply and food productivity.

3.6.3 Food and socio-metabolic risks

In Caribbean SIDS, the tourism sector is a major driver for resources use as they represent the most tourism-dependent region globally (Ford & Dorodnykh, 2016; WTTC, 2022). During 2019, the values of travel & tourism contribution to GDP were above 80% for Antigua and Barbuda, and 60% for Aruba and St. Lucia (WTTC, 2022). In the region, tourist arrivals have increased close to 15% between 2010 and 2014 with numbers close to 80% for Haiti, 30% for Aruba, and 25% for Dominican Republic (UNWTO, 2015). However, accounting for the rapid globalization of traded goods, changes in consumer habits, climate change and the growth of the tourism industry, the transmission of foodborne hazards and diseases within and between Caribbean SIDS and abroad could also increase (Clarke & Roopnarine, 2022; Guerra et al., 2016) (see Table 5, Food Self-sufficiency). A large majority of Caribbean SIDS have adopted international standards on quality control for laboratory testing and calibration, but only few have been actually accredited by an official body (Guevara et al., 2014). With limited resources available, the regional monitoring systems of the agrifood chains are likely to be deficient. Studies indicate outbreaks and infections from foodborne pathogens in island populations and tourist visitors (M. D. Gray et al., 2015; Kendall et al., 2012; Mughini-Gras et al., 2014; Tighe et al., 2012). Island governments thus need to prioritize food safety systems in all stages of production, processing, storage, distribution and trade that assess the incidence and prevalence of pathogens linked to foodstuffs (FAO et al., 2021; FAO & WHO, 2005). By doing so, the incidences of cases could be minimized, saving lives and avoiding the economic burden from costly medical bills (Guerra et al., 2016; B. Lee, 2017; Scharff, 2012).

Food security is heavily dependent on sustainable, resilient, inclusive, and efficient systems of production and consumption (FAO, 2017a). Nonetheless, in Caribbean SIDS, the access to affordable foods that support healthy dietary patterns not only at a single point in time but also across the lifespan and possibly for future generations remains a pressing issue (see Table 5, Food Access). Healthy diets are driven by preferences, but also by prices as these foodstuff are mostly imported (Massa, 2021). Today, close to 50% of the population in Caribbean SIDS are unable to afford a healthy diet due to elevated costs or unavailability (FAO et al., 2021). This situation is strongly linked to the prevalence of severe levels of food insecurity as these have been climbing slowly, now affecting 37.6% of the Caribbean SIDS population compared to the LAC averages of 11.3% and global averages of 10.5%. Moreover, although some progress has been made, the prevalence of undernourishment in the Caribbean region is currently almost double the global average of 9% (ibid).

Deficiencies in food security and nutrition are an outcome of several complex internal and external factors (e.g., island geography, governance deficiencies, institutional constraints, environmental and economic vulnerabilities) which can result in severe consequences on the overall wellbeing of the population (Massa, 2021; Mohammadi et al., 2022). Food insecurity and malnutrition impact social and economic progress and materializes among the population as physical growth and mental development deficits, morbidity, increased risk of death, poor school performance, and low work productivity among others, which in the long run could impair human development and even trap the population in an intergenerational cycle of malnutrition, poverty and health issues (ECLAC, 2017; Ruel, 2013) (see Table 5, Food Access). For Caribbean SIDS, we can observe a shift towards an increased dependency on food imports of non-traditional, lower quality diets, with lower intake of vegetables and fruits, an increased intake of food from meat and especially of nutritionally inferior processed foods with high caloric content (FAO, 2021a, 2022a). This shift away from local, often healthier foods has led to the loss of a healthier and productive life (FAO, 2017a; UN, 2010) (see Table 5, Food Consumption). The human potential that is lost due to poor health and the burden of disease is measured through the Disability-Adjusted Life Years (DALY) indicator, which equals to one lost year of healthy life because of either premature death or disease or disability (Roser et al., 2021; WHO, 2022a). In the Caribbean SIDS, DALYs resulting from non-communicable diseases (NCDs) grew from 67% to 74% between 2000 and 2017, compared to a global average of 60% in 2017 (IHME, 2022). More than 40% of the total DALYs attributed to NCDs fall into only 3 categories: cancers, diabetes & kidney diseases, and cardiovascular diseases (ibid), which are the leading cause of death and disability among Caribbean SIDS (CARICOM, 2016; CARPHA, 2021).

Food self-sufficiency in Caribbean SIDS is declining, as domestic food production is insufficient to meet the demand (see Table 5, Food Availability and Self-sufficiency). With a narrow agricultural resource-base, the per capita arable land in Caribbean SIDS is around 0.06 ha/cap, three times less than that of the least developed countries (LDCs) and developing countries (The World Bank, 2022b). This can be partially explained by the absence of an adequate accessible volume of water for irrigation and changes in land-use in favor of urbanization. Moreover, the combined effects of structural policy adjustments, climate variability and extremes like storms, droughts, excessive rains, and loss of top soil due to flash floods are also a significant factor in food production decline, which can cascade into negative effects on food prices, value chains, water supplies and livelihoods, and overall food security (FAO, 2020a; FAO et al., 2018, 2021; Rahman et al., 2022; Singh et al., 2022). In monetary terms, Caribbean SIDS import more than 80% of their domestic food supply needs (Dorodnykh, 2017), while deficiencies in the agri-food supply chain have contributed to food losses of more than 50% of supply (Kaza et al., 2018). Considering their heavy food imports dependency and elevated food losses, these countries are also exposed to high foodstuff bills that in the long run will further put at risk their resource-security levels (WFP, 2022). Moreover, disruptions in the global supply chain (e.g., due to the war in Ukraine at the beginning of 2022) and price volatility have sharply affected commodity prices in the Caribbean, especially for foodstuffs (Ewing-Chow, 2019a; The World Bank, 2022m). A shift toward food self-sufficiency in small islands as a food security and resilience strategy would then require an approach that is intersectional, flexible, adaptive and that is supported by an effective regulatory and institutional framework that allow for context-specific implementations (Dorodnykh, 2017; Mohammadi et al., 2022; Rahman et al., 2022).

To address the identified SMRs of obesity and related diseases while at the same time achieving SDG 2 of food security and nutrition will require coordinating efforts from different stakeholders at both the local, and international level. Benefits are achieved through promoting inclusive policies as well as social protection programmes for the most vulnerable groups, and that support locally manufactured foods (e.g., by improving the local food supply chain and reducing overall prices) in favor of traditional healthier foods. Nature-positive production and supply models (e.g., system-based conservation agriculture, river basin management, bio-inputs, integrated soil fertility management, soil and water conservation and nutrient recycling) are also important to improve market conditions and to increase food security while at the same time increase resource-security (e.g., through prevention of soil degradation, water and energy consumption, etc.), which can also have important benefits in terms of both food productivity and sustainability (Hodson et al., 2021; Massa, 2021).

3.7 Summary of findings on the resource (inter)dependency of critical resources in small islands from a socio-metabolic risk perspective

The study presented in this Chapter offers the first attempt at operationalizing the concept of SMRs. By means of characterizing the shifting baseline of 14 Caribbean SIDS with respect to water, energy, and food, and the dimensions of resource availability, access, consumption, and self-sufficiency, the study has identified potential SMRs in need of addressing. This methodology expands knowledge on socio-metabolic research and the WEF-nexus at country-and regional level for Caribbean SIDS, and provides baseline data for policy and other stakeholders to better understand critical resource dynamics. In addition, it offers a general overview of the potentials that this methodology may offer in identifying SMRs.

On this Chapter, it is demonstrated the immediate need for an integrated approach to manage critical resources like water, energy and food in resource-stressed contexts like Caribbean SIDS. Maximizing resource-security, minimizing trade-offs, and improving the linkages between critical resources may offer synergistic solutions that can be leveraged to mitigate inherent risks. Understanding the overall dynamics of critical resources to identify, manage and mitigate SMRs is crucial for SIDS. By doing so, we could design a strategy to build resilience, adapt to, anticipate, resist, and recover from climate change impacts and shocks, and to avoid cascading dysfunction of environmental, economic, and social systems.

Meanwhile, as Caribbean SIDS share common technical, institutional and regulatory barriers and vulnerabilities, they also vary greatly in terms of their resource-bases, population, economic development, infrastructure, health, and more. Regional average figures tend to mask these variations across individual countries, as such, one also needs to consider trends and context when it comes to country-level planning. Along with regional cooperation, interventions must consider the wide range of realities within the region to properly identify potential barriers and openings for positive transformative change.

Notably, by analyzing SMRs within the overall resource dynamics could be key to achieve the global UN Sustainable Development Goals 2, 6, and 7 with greater confidence and certainty. One must recognize the existing and potential impacts of SMRs arising from alterations to human and natural systems in SIDS, including increases in droughts, floods, and some other types of extreme weather; sea level rise; and biodiversity loss; and also the trends of resource-use, including low food production and high processed foods imports and consumption, water quantity and quality challenges, and high dependence of fossil fuels, etc. Making stakeholders aware of these risks is key to inform and enable them to employ and implement sustainable and efficient solutions and practices that could aid in minimizing SMRs and that generate synergistic effects in the long run (FAO, 2018).

With regards to our methodology, our approach has contributed to broaden our understanding of the resource-use dynamics in the island context. Nonetheless, future research should also look beyond the analyzed dimensions of availability, access, consumption, and self-sufficiency, and include other dimensions like the social and political *(un)acceptability* of socio-metabolic risks and mitigation strategies. Within this context, risk *acceptability* is defined as the "level of potential losses that a society or community considers acceptable given existing social, economic, political, cultural, technical and environmental conditions" (INEE, 2022). For SMR mitigation strategies to be better evaluated, these need to analyze the costs and benefits, including in terms of risk *acceptability* while considering the socio-economic context in which these will be applied, together with the needs, issues, and concerns of the stakeholders involved. Individuals, communities and government have different perceptions about what risks and mitigation strategies are acceptable or tolerable, depending on their experience, knowledge and the information they receive. Given that few studies attempt to understand and/or incorporate the perceptions and preferences by small island communities and peoples in terms of *acceptability* of risks and mitigation strategies, the inclusion of this dimension would be valuable to consider. Incorporating it in the analysis could also provide extra information and advice to the government and community about the risk faced and about what actions to take to minimize risk to "acceptable" levels. Moreover, by aligning these solutions with the values, needs, preferences and expectations of the society and searching for socially acceptable and desirable futures can help bridge the gap between research and implementation of strategies to minimize risks (Stephanides et al., 2019).

Chapter 4: The significance of resource-use patterns and socio-metabolic risks to build resilience in small islands[2]

4.1 Abstract

Resource-use patterns may entail systemic risks and cascade effects, which consequently inhibit the ability to deliver socioeconomic services. Identifying resource-use patterns exhibiting systemic risks and reshaping their combinations is a potential lever in realizing the transition to a sustainable, resilient, and resource-secure system. Using an island context to assess the quantity and composition of resource throughput enables a more comprehensive analysis of these risks. This Chapter presents the first mass-balance account of socio-metabolic flows for The Bahamas in 2018, to identify socio-metabolic risks and cascading effects. Socio-metabolic risks are systemic risks related to critical resource availability, material circulation integrity, and (in)equities in cost and benefit distributions. The economy-wide Material Flow Accounting framework (ew-MFA) was utilized to map the patterns of material flows across the entire economy. In 2018, annual direct material input (DMI) was estimated at 9.4 t/cap/yr, of which 60% were imports. High masses of waste (1.4 t/cap/yr) remained unrecovered due to the lack of recycling. Total domestic extraction (DE) were dominated by non-metallic minerals with more than 80%, while marine biomass makes up barely 1% of total DE flows. Due to its linear, undiversified metabolism, and heavy imports dependency, the system is susceptible to SMRs and cascading effects including low levels of self-sufficiency, high vulnerability to shocks, commodity price fluctuations, threats to sensitive ecosystems, health impacts, and economic losses, among others. The results of this Chapter highlight that a holistic resource management strategy and nature-based solutions (NbS) that consider the trade-offs and synergies between different resource-use patterns are critical when exploring potential plans for metabolic risks reduction.

4.2 Introduction

The unprecedented growth in the use of resources has caused global material extraction to quadruple since the 1970s, from around 22 billion tonnes to 100 billion tonnes in 2020, with projections reaching

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[2] The contents of this section of the Chapter have been incorporated within a paper that has been submitted for publication. 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*, 1-17. https://doi.org/10.1111/jiec.13369. Minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

around 180 billion tonnes by 2050 (Circle Economy, 2020; Krausmann et al., 2018; UNEP, 2016; UNEP & IRP, 2017). Meanwhile, the circularity rates of materials re-entering the economy at the end of their lifecycle remain low, slightly declining from 9.1% in 2018 to 8.6% in 2020 (Circle Economy, 2020). Similarly, global energy use almost tripled from 224 EJ in 1971 to 624 EJ in 2019 and is estimated to hit 879 EJ by 2050 (British Petroleum, 2021; Schandl et al., 2016; Smil, 2017, 2017; World Energy Council, 2013). While these resource-use dynamics may have brought about an improvement in global material standards of living, it has come at the cost of destabilizing the Earth system on which we depend (IPCC, 2018; Rockström et al., 2021; Steffen et al., 2015; Steffen & Morgan, 2021; UNEP & IRP, 2017; Wiedmann et al., 2020).

The situation becomes even more critical in concentrated geographic settings like SIDS. SIDS are often characterized by sustainability challenges like limited resource-bases, reduced waste absorption capacity, geographic dispersion, natural and built environment that is progressively been caught between rising sea levels and already limited available inland areas (coastal squeeze), and geographic isolation from markets which impact connectivity and the ability to mobilize people and resources (Deschenes & Chertow, 2004; UNCTAD, 2021). SIDS often rely on imports for up to 80–90% of their basic needs (Bradshaw et al., 2020; Dorodnykh, 2017; FAO, 2019; IRENA, 2014; Symmes et al., 2019) and consistently rank high on various vulnerability indices like The World Risk Report (Aleksandrova et al., 2021), The Commonwealth Universal Vulnerability Index (The Commonwealth Secretariat, 2021), and the Commonwealth Vulnerability Index for Developing Countries . For many SIDS, social and economic impacts have combined with the adverse effects of environmental impacts such as climate change and sea level-rise, resulting in compounding shocks, which often amplify pre-existing vulnerability levels and sustainability challenges (IMF, 2021; Sachs et al., 2021; Thomas et al., 2020).

A major gap in the island socio-metabolic research literature is investigations of the risks embedded in the metabolic profiles of island socio-economic systems. Socio-metabolic risks are systemic risks related to critical resource availability, material circulation integrity, and (in)equities in cost and benefit distributions. Specific resource-use patterns could quickly lead to severe metabolic risks and cascading effects and become a metabolic trap, which in turn can inhibit progress towards greater resource security, self-reliance, and the system's ability to deliver necessary societal services. In some instances where high metabolic risk exist, the system's ability to organize its own social metabolism is severely compromised, thus potentially leading to the system's socio-metabolic collapse (Singh et al., 2020, 2022). A socio-metabolic collapse is usually characterized by crossing a threshold or tipping point, defined as a point at which the number of small changes or incidents (on the social metabolism's organization) over a period of time reaches a level where a further small change has a sudden and very great effect on a system (Oxford University Press, 2022) that is oftentimes irreversible. Reaching this threshold or tipping point can be due to biophysical (e.g., overexploitation of natural resources), social phenomena (e.g., resource-insensitive models of development), or a combination of both (Petridis & Fischer-Kowalski, 2016) (see Figure 6).

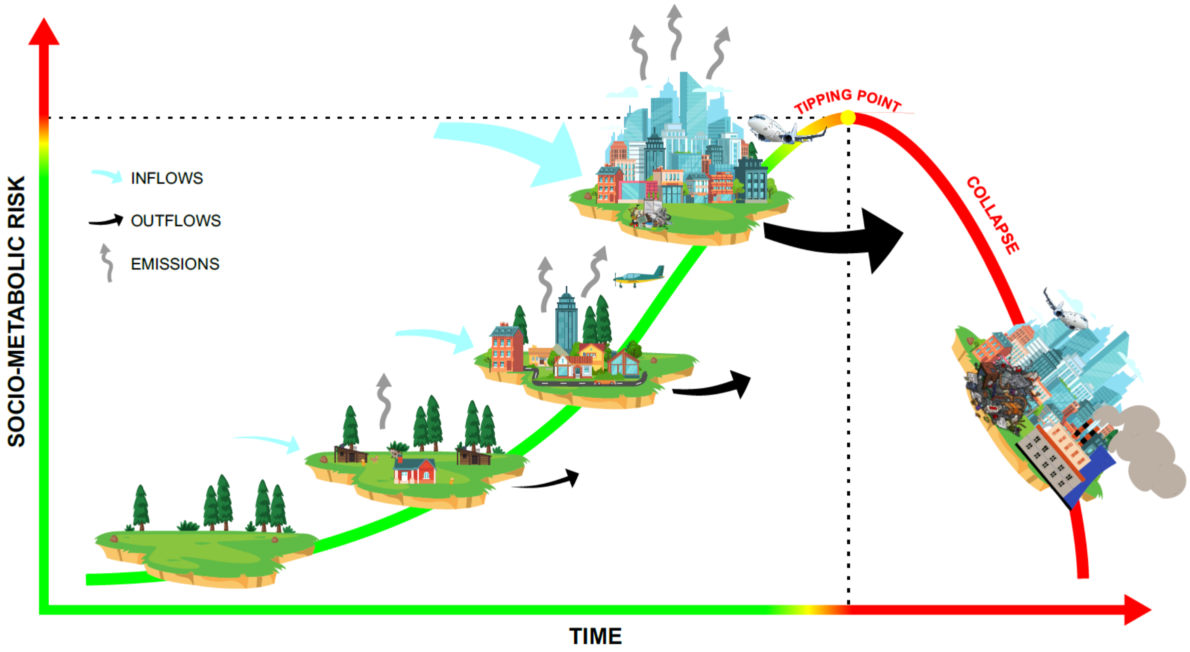

Figure 6 – Conceptual figure of tipping points and system's socio-metabolic collapse due to increased socio-metabolic risks

Examples of this in small islands include St. Eustatius in the Caribbean, where soil erosion caused by goats grazing and marine resource extraction (e.g. fishing for conch) both impact the marine ecosystem, which is a prime source for tourism in the island (Polman et al., 2016); Nauru in the Pacific Ocean showed signs of exploitation of a single key resource (phosphate mining), which in turn had devastating environmental consequences (McDaniel & Gowdy, 2000; Pollock, 2014); and in Bonaire in the Caribbean, tourism-related coastal development and high import dependency of basic needs (e.g. water, energy, and food) is pressuring island resilience through habitat loss, waste generation, and high import costs (Slijkerman & van der Geest, 2019). Resource-use patterns can contribute to global environmental change but also determine their own vulnerability or resilience to those changes. Societies could adapt to climate change, build system resilience and achieve an improved standard of living at the lowest environmental costs by identifying and reconfiguring resource-use patterns that exhibit potential systemic risks (Singh et al., 2022).

Previous research has demonstrated the value of Material Flow Analysis (MFA) as an innovative means of measuring levels of socio-economic metabolism in the context of small islands. Most socio-metabolic research focuses on inflows (e.g. Bahers et al., 2022; Chertow et al., 2020; Eisenhut, 2009; Krausmann et al., 2014; Rahman et al., 2022; Singh et al., 2001), very few on biophysical stocks (e.g. Bradshaw et al., 2020; Noll et al., 2019; Symmes et al., 2020) and outflows (e.g. M. J. Eckelman et al., 2014; Elgie et al., 2021; Mohammadi et al., 2021), however only one uses a mass-balanced approach to explore the potential for a “circular economy” in an island context (Noll et al., 2021).

The study presented in this Chapter aims at identifying socio-metabolic risks and cascading effects for the Caribbean SIDS of The Bahamas. The Bahamas has identified some immediate challenges it needs to address: a slowdown in social progress, governance arrangements that do not support a modern Bahamas, a highly vulnerable built and natural environment, and a highly vulnerable, undiversified, and underperforming economy (Government of The Bahamas, 2016b). This has led the country to develop strategies that prioritize human wellbeing, natural resource exploitation, climate change, and sustainable resource-use to catalyze sustainable economic development and risk minimization (Bahamas Development Bank, 2018; Climate Ambition Alliance, 2019; Government of The Bahamas, 2015, 2016b; WHO, 2021). The country, with its narrow resource-base, large imports requirements, heavy dependence on tourism, extensive areas of flatland, and high concentration of coastal inhabitants (Bahamas Department of Statistics, 2017; Lutter et al., 2018; The Bahamas Natural Resources Foundation, 2021; WHO, 2021), serves as a great opportunity to explore the linkages between dynamics of resource use and associated systemic risks.

The study presented in this Chapter offers the first mass-balance account of socio-metabolic flows aimed at investigating the systemic risks and cascading effects embedded in the metabolic profile of an island’s socio-economic system. A mass-balance study of The Bahamas for the year 2018 was conducted by applying the economy-wide Material Flow Analysis (ew-MFA) framework and circularity accounting frameworks. The study presented in this Chapter is motivated by the following questions: 1) What characterized the metabolic profile of The Bahamas in 2018? 2) What are the inherent systemic risks and cascading effects associated with the country’s resource-use patterns? 3) What are potential options for reconfiguring the country’s resource-use patterns and build resilience?

Thus, the results of this Chapter's analysis further expand the literature on islands socio-metabolic research, by innovatively incorporating both MFA and circularity principles in the account of socio-metabolic flows to provide a broader view of potential SMRs and cascading effects for a Caribbean SIDS. The Bahamas' metabolic profile is identified and compared to other island socio-economic systems and the interdependence between the dynamics of resource-use and associated systemic risks is investigated. Further, empirical insights are provided to define future strategies for metabolic and systemic risks reduction in The Bahamas, advising to plan for resilience, and to implement monitoring approaches that fully incorporate and maximize the local capacity to help in the transition toward a sustainable, resilient, and resource-secure system.

4.3 Methodological framework

The system boundary of the economy-wide Material Flow Analysis (ew-MFA) is consistent with the geographical boundary of The Bahamas. The study adopted the most recent ew-MFA accounting guidelines from EUROSTAT (European Commission, 2018), complemented by the circularity accounting frameworks proposed by Mayer et al., (2019) and Haas et al., (2020). The study adopts a combined quantitative and qualitative approach. The quantitative part measures the biophysical flows of masses and composition of materials that flow through the economy to determine the metabolic scale and circularity rates within the case-study's socio-economic system. The qualitative part is performed through an assessment of the quantitative part of the ew-MFA and circularity indicators in which we interpret the associated potential metabolic and systemic risks as well as opportunities to develop and implement risk mitigation and adaptation strategies in the system. This was done in such a way due to not having an established definitive index, scale, or threshold specifically for evaluating SMRs.

The study recognizes the role that service sectors have on the biophysical flows. Even though service sectors (e.g. tourism) may not directly induce biophysical flows, they do have an indirect impact on these. On one hand you have beneficial outcomes such as income generation and job creation arising from service sector activities (e.g., tourism), but at the same time these require the allocation of resources for those activities, which translates into more flows of materials to grow and maintain stocks, to continue operations, etc. and that influence on the overall biophysical flows. Notwithstanding this, the analysis of service sectors was out of the scope of this analysis. Figure 7 shows the general framework used for the ew-MFA.

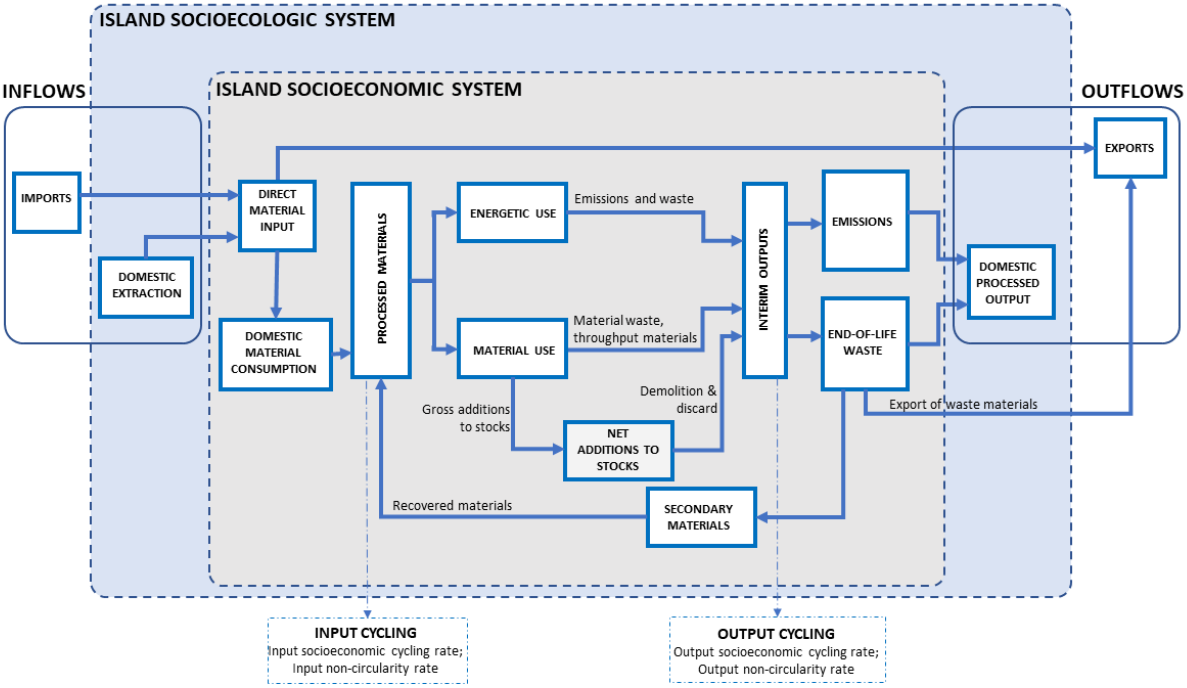

Figure 7 - General Framework for the ew-MFA in The Bahamas. Adapted from Haas et al. (2020) and Mayer et al. (2019)

All inflows and outflows for the year 2018 across all four main aggregated material flow categories as established by the guidelines from EUROSTAT (European Commission, 2018) were considered, namely: fossil fuels, biomass, metal ores, and non-metallic minerals. A fifth category of “other” complex goods and their materials that are not clearly attributed to any of the other four categories in the official statistics was included, e.g., miscellaneous furniture, boilers, vehicles, electrical machinery, and clothing. Table 6 provides an overview of the materials included in each material category. Using data on trade and domestic production, waste masses, waste composition, and recycling, the study mapped and traced the material flows in the socio-economic system. Information on in-situ material–energy use, waste, and recycling efforts was obtained to understand the resource flow status and circularity rates in The Bahamas. More detailed descriptions of the used data, their sources, and processing for this Chapter can be found in Section 4.3.2.

Table 6 - Main Material Categories and Materials Considered in the Study.

Main material categories	Materials included
Fossil fuels	Mineral fuels, mineral oils and products of their distillation, petroleum gases and other gaseous hydrocarbons, coal, spirits for motors, aviation turbine fuel, kerosene oil, diesel, fuel oil, base oil, and others
Biomass	Crops, crop residues, wood, wild catch, and other biomass
Metals	Iron, copper, nickel, lead, zinc, tin, precious metals, aluminum, uranium and thorium, other non-ferrous metals, and other miscellaneous products mainly composed of metals
Non-metallic minerals	Sand/gravel, salt, limestone, clays, gypsum, chalk and dolomite, slate, fertilizers, and other non-metallic minerals
Other	Materials not assigned to the previous four material categories, or which are not elsewhere specified (e.g., furniture, vehicles, machinery, clothing, and other miscellaneous products)

Source: Adapted from European Commission (2018)

4.3.1 Scale and circularity indicators for the biophysical monitoring of the economy

A series of indicators for material input and output across all material categories were calculated to measure the metabolic scale and circularity rates, as well as to identify potential metabolic risks. Scale indicators measure physical accounts and balances of mass flows, resource use, stocks, and waste and emissions outputs in mass, which serve to plan for resource efficiency and conservation as well as sustainable resource management. Similarly, circularity indicators measure rates of flows related to the recovery of materials into the economy. In a circular economy, energy provisioning depends on renewable sources and moves away from fossil fuels. Additionally, the recovery and utilization of waste materials is a key element in the development of a robust circular economy. As such, circularity indicators at both system input and output level may contribute to a more general vision of material flows as these can serve as proxies to investigate the pressures and metabolic risks associated with resource use patterns. Table 7 shows an overview of these indicators.

Table 7 - Overview of the Scale and Circularity Indicators and their Definitions for the Physical Monitoring of the Economy

	Indicators	Description
Scale [kt/yr]	***Material input indicators***	
	Domestic extraction (DE)	All materials extracted from the domestic environment
	Imports	Inputs of goods originating from outside the national economy
	Direct material inputs (DMI) = DE + imports	Input of materials into the national economy originating from the domestic environment and the rest of the world
	Material use indicators	
	Domestic material consumption (DMC) = DMI – exports	Total amount of materials that are directly used in a national economy
	Processed materials (PM) = DMC + SM	All materials processed domestically
	Secondary materials (SM)	Includes materials recovered from end-of-life waste which are reintroduced into the domestic economy
	Energetic use (eUse)	Share of PM that provide energy for technical applications as well as for livestock and human metabolism (feed and food)
	Material use (mUse)	Share of PM that is used for its material properties
	Material stocks indicators	
	Gross additions to stocks (GAS)	All materials going into material stocks (lifetime greater than one year)
	Net additions to stock (NAS) = GAS – Demolition & Discard	Net amount of material added to the stocks per year

	Material output indicators	
	Exports	Outputs of goods and materials to other economies
	Demolition and discard (D&D)	Quantity of materials removed from material stocks after their service lifetime
	Interim outputs (IntOut)	Includes all materials that are accounted as an output from the socio-economic system before divided into Emissions and End-of-Life waste
	Domestic processed outputs (DPO)	All materials that are released back into the environment as a result of consumption and production processes
	Emissions	The part of the DPO corresponding to emissions, whether from combustion processes or metabolic processes of livestock and humans
	End-of-life (EoL) waste	The part of the DPO corresponding to solid materials that can no longer be cycled back to the economic system as secondary materials and have reached the end of their service lifetimes
Circularity [%]	***Input circularity indicators***	
	Input socio-economic cycling rate (ISCr) = (Secondary Materials ÷ PM) × 100	Share of Secondary Materials reintroduced through socio-economic processes into the economic system
	Input non-circularity rate (INCr) = (Fossil energy carriers ÷ PM) × 100	Fossil energy carriers as share of PM
	Output circularity indicators	
	Output socio-economic cycling rate (OSCr) = (Secondary Materials ÷ IntOut) × 100	Share of Secondary Materials present in IntOut
	Output non-circularity rate (ONCr) = (Fossil energy carriers ÷ IntOut) × 100	Fossil energy carriers as share of IntOut

Sources: European Commission (2018); Haas et al. (2020); Hotta & Visvanathan (2014); Jacobi et al. (2018); Mayer et al. (2019)

4.3.2 Economy-wide MFA: Data review and sources

Scale Indicators - Data on masses of domestic extraction (DE) from official Bahamian statistics were insufficient. As such, DE flows were captured through different data sources. The Energy Information Administration (EIA, 2021) provides data on fossil fuel production, consumption, and trade. The FAOSTAT statistical database (FAO, 2021a, 2021b) was the main data source for the biomass category. The UN IRP Global Material Flows Database (UNEP & IRP, 2022) was referred to for non-metallic minerals and the British Geology Survey (Brown et al., 2021) for metals and non-metallic minerals.

Import and export flows include traded goods made of primary and processed materials. Although the country releases quarterly and yearly reports on foreign trade, these only contain the top 25 commodities ranged by value ($) instead of mass (weight) (Government of The Bahamas, 2022). Therefore, the study accounted only for those goods reported in the official international trade statistics platform of the United Nations (United Nations Statistics Division, 2018) and enumerated using clear mass units. These were disaggregated using the Harmonized System (HS) 2012 for classifying goods using six-digit codes.

Processed materials (PM) are used either for energy (eUse) or for their material properties (mUse). PM are calculated including data on waste recycling efforts in The Bahamas. The share of PM utilized for energy use (eUse) includes all flows utilized for provisioning energy for technical applications as well as for livestock and humans (feed and food). Technical applications include fossil fuels and biomass for combustion (wood fuel and coal). Food and feed include goods of animal and vegetal origin as well as processed foods. Material use (mUse) was calculated as the difference in mass between PM and eUse.

Masses and composition of solid waste from official Bahamian statistics were not available. As such, the most recent estimates (2016) from the World Bank Group on municipal solid waste (MSW) generation rates for The Bahamas as well as of MSW composition in Latin America and the Caribbean (LAC) region (Kaza et al., 2018, p. 54) were taken for this analysis. The shares of total solid waste streams (MSW and Demolition & Discard (D&D)) in The Bahamas were taken from estimates from the InterAmerican Development Bank (IDB, 2018, p. 53).

Regional or country-specific characterization of D&D for The Bahamas is non-existent. As the building code of The Bahamas is based generally on the South Florida Building Code (Ministry of Works & Utilities, 2003), the study assumed that D&D waste composition mentioned in the US EPA report "Construction and Demolition Debris Generation in the United States, 2014" (U.S. Environmental Protection Agency, 2016, p. 18) was also applicable in this case study.

Estimates on recycled materials from official Bahamian statistics were limited. Recycling, if any, is managed mainly through non-profit organizations in the country, and the data collection and reporting on masses and composition is usually not publicly available. To account for this, major efforts were undertaken to contact recycling non-profit organizations such as WasteNot Bahamas Limited, Cans for Kids Bahamas, and Bahamas Waste Limited.

Interim outputs (IntOut) include emissions and waste from eUse, mUse, and and D&D. The eUse component of IntOut comprised emissions and ashes from fuel combustion for both biomass and fossil fuels, along with biomass food waste obtained from total MSW. The mUse component includes all other material waste from MSW except for food waste. Waste from Gross Addition to Stocks (GAS) considers the total mass of D&D.

GAS was calculated as the difference between mUse and material waste from MSW not including biomass from food waste. The difference between GAS and D&D equals the net addition to stocks (NAS).

End-of-life (EoL) waste considered total D&D, total MSW, ashes from fossil fuel and biomass combustion, and livestock excrement resulting from metabolization of biomass feed. Ash masses were based on typical post-combustion ash content per fuel type. Excrements were estimated by considering the number of livestock animals and by applying coefficients of manure generation per livestock.

Masses of emissions resulting from fossil fuels and from biomass were estimated using the principles of mass balance. The former was estimated as the difference between the total mass of eUse and the total mass of fossil fuel ashes from combustion, while the latter was estimated as the difference between the total masses of biomass share in IntOut (ashes from combustion, biomass waste, and excrement) and the total mass of biomass share from end-of-life waste. The sum of Emissions and End-of-Life (EoL) waste equals Domestic Processed Output (DPO).

The rest of the indicators were calculated using the principles of mass balance through a combination of data on DE, imports, exports, MSW, D&D, and recycling masses, among others (see Table 7).

Circularity Indicators - Both the input non-circularity rate (INCr) and the output non-circularity rate (ONCr) quantify the fossil energy carriers' share in PM and IntOut, respectively. In the case of the socio-economic cycling rate (ISCr) and output socio-economic cycling rate (OSCr), these measure the share of secondary materials in the system input and output, respectively (Haas et al., 2020; Mayer et al., 2019). These indicators were calculated through data on recycling masses by category (Secondary Materials) and fossil energy masses, divided by the masses of PM or IntOut.

General Considerations – The analysis of this Chapter relied primarily on international data sources like the UN IRP Global Material Flows Database, the World Mineral Production report from the British Geology Survey, the FAO, and the UN Comtrade database. A combination with available national statistics (Government of The Bahamas, 2019) as well as by contacting local government officials and non-governmental organizations (NGOs) allowed us to cross-check, verify, and improve datasets where possible. A semi-quantitative assessment of data quality based on an adapted "pedigree matrix" (Allesch & Rechberger, 2018) is presented in the Appendix B. The main indicators of DE, Imports, and Exports and their derived indicators exhibit a good data quality as these stems directly from established international statistical data sources. The lack of good waste data (due to assumptions and limited data availability) affects the ability to effectively assess masses and composition of outflows. Nonetheless, the general messages that this study aims to communicate can still be seen as valid.

Major efforts were undertaken to verify the various data sources and find the most accurate and up-to date information available. Most of these data sources have been compiled and processed from sources believed to be reliable, however, it is advised that these should be considered with a degree of caution due to global inconsistencies in definitions, data collection methodologies, and completeness. Section 6.4.1 provides further details on datasets limitations. Appendix B provides detailed data compilation methodologies for the different indicators utilized in this Chapter. Also, Appendix B provides extra information of Chapter 4 about data sources for DE, Imports and Exports, and estimates of outflows, and provides an overview of data quality for the main indicators. Additionally, it provides figures of disaggregated masses of flows for the mass balance and provides a comparison of waste generation across the Caribbean SIDS. Moreover, it provides data in tabular form with socio-metabolic indicators utilized for the mass balance and that were utilized to elaborate Figure 8 in this Chapter.

In the results section of this Chapter one can see that part of the imported flows simply pass through the economy, first being imported and then re-exported. In this case, The Bahamas is exposed to the Rotterdam effect as it serves as a middle point in the transit of flows of goods to other economies. This study recognizes that the analysis presented in this Chapter 4 could have benefited from a more disaggregated and granular information on material flows and especially through a more profound analysis of the Rotterdam effect. However, it also recognizes that separately accounting for these throughflows that simply pass through the economy, and for all material categories, posed a significant challenge as this specific information was not explicitly reflected in the consulted international data sources for The Bahamas. Bahamas Customs assisted with quarterly and yearly reports on foreign trade (imports and exports), however these only contained the top 25 commodities ranged by value ($) instead of mass (weight) and excluded all other commodity flows. Accordingly, the analysis did not make a distinction between these throughflows and accounted for the total material flows imported and exported as presented in the consulted international data sources regardless of origin or destination.

4.4 Results

4.4.1 Scale indicators

Figure 8 shows the ew-MFA Sankey diagram for The Bahamas for 2018.

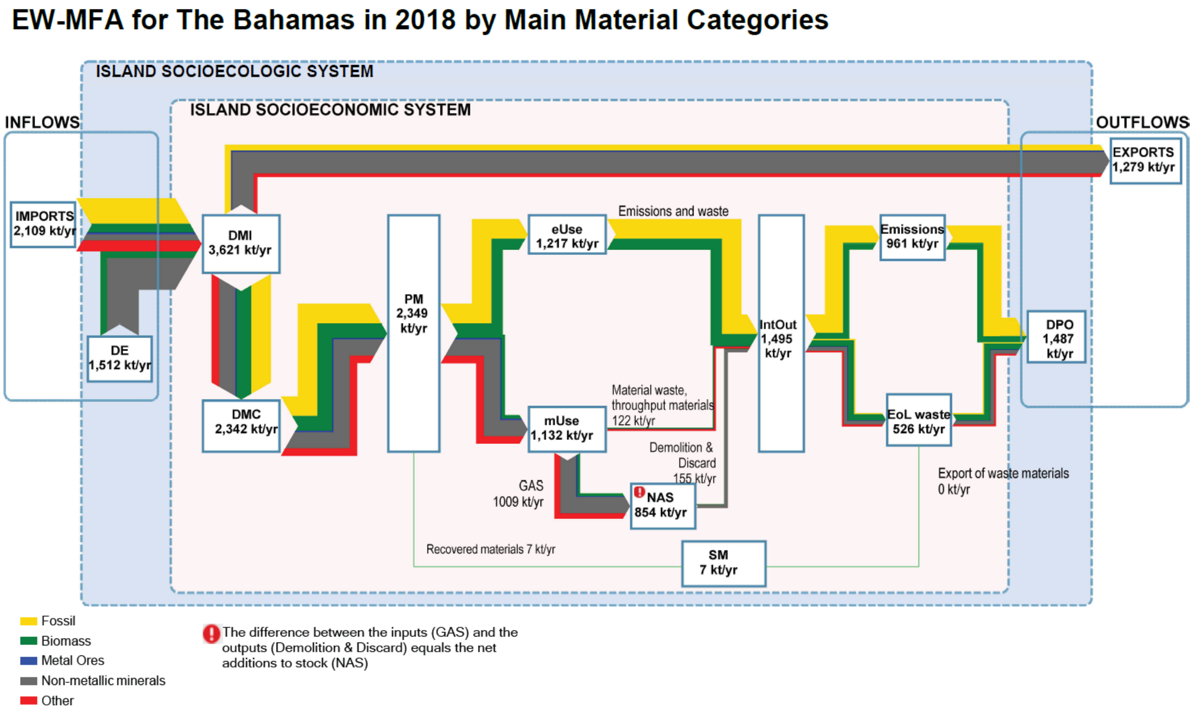

Figure 8 - Estimated ew-MFA for The Bahamas during the year 2018. Units in kilo tonnes per year [kt/yr]. Source: Current study. Indicators: Domestic Extraction (DE), Direct Material Inputs (DMI), Domestic Material Consumption (DMC), Processed Materials (PM), Secondary Materials (SM), Energy Use (eUse), Material Use (mUse), Gross Additions to Stocks (GAS), Net Additions to Stocks (NAS), Interim Outputs (IntOut), End-of-Life (EoL) waste, Domestic Processed Outputs (DPO).

In 2018, the Bahamian economy resembled that of a linear socio-metabolic profile with material flows mainly directed to final consumption and high waste generation that remained unrecovered. The country showed a higher reliance on external sources for energy carriers and manufactured goods due to the lack of domestic supply. The country's extractive resource patterns are focused on a few key natural resources, while the economy's exports are mainly based on domestically extracted non-metallic minerals. Materials that are released back into the environment as emissions and waste (DPO) represent almost two-thirds of the total resource consumption (DMC).

DMI was estimated at 3,620 kt/yr of which 60% were imports. As the population in 2018 was around 385,600 habitants (Worldometer, 2022a), per capita values of DMI are close to 9.4 t/cap/yr. Total DE was estimated at 1,500 kt/yr or 3.9 t/cap/yr. Non-metallic minerals represented more than 80% of the total DE. Of this, 70% was salt and 30% was aggregate materials (sand and gravel). For DE, the total biomass was estimated at 250 kt/yr or 0.7 t/cap/yr. Of this, around two-thirds were utilized for food or feed, while less than one-third was directed to either energy use or construction processes (industrial timber and fuelwood). Marine biomass extraction amounted to only 11 kt/yr, less than 5% of the total biomass DE. Imports were estimated at 2,100 kt/yr or 5.5 t/cap/yr. Half of total imports were fossil fuels, which were directed towards energy use or exports.

Total processed materials (PM) were estimated at 2,350 kt/yr or 6.1 t/cap/yr. Of this, PM was divided almost equally between eUse and mUse. For eUse, around 60% comprises imported fossil fuels while the rest comes from biomass. For mUse, the largest flow is from non-metallic minerals, which represent almost 60% of the total mUse. Furthermore, 90% of the total mUse was used for building up stocks (GAS), comprising mainly commodities such as cement, aggregates, furniture, and miscellaneous products.

Total exports and DPO were estimated at 1,300 kt/yr (3.3 t/cap/yr) and 1,500 kt/yr (3.9 t/cap/yr) respectively. Exports were heavily influenced by non-metallic minerals, particularly salt (around 850 kt/yr), which represents around two-thirds of total exports. Minimal masses of biomass exports (1% of the total) were focused on marine products, timber, and fuelwood. High masses of waste (530 kt/yr or 1.4 t/cap/yr) remained unrecovered due to virtually no recycling (1%), while exports of waste materials were negligible. DPO flows were dominated by fossil fuels, which represent around half of the total DPO, and by biomass flows, which represent around one-third of the total DPO. Moreover, emissions and EoL waste represent two-thirds and one-third of the total DPO, respectively.

4.4.2 Circularity Indicators

Complementing the understanding of metabolic risks in the island context, this Chapter’s sub-section presents circularity indicators calculated in this case-study (see Table 8).

Table 8 - Overview of Circularity Indicators in The Bahamas for 2018.

Indicator	Circularity [%]
Input socio-economic cycling rate (ISCr)	
Fossil products	0
Biomass	1.1
Metals	0
Non-metallic minerals	0
Other	0.1
Total	0.2
Output socio-economic cycling rate (OSCr)	
Fossil products	0
Biomass	1.4
Metals	0
Non-metallic minerals	0
Other	0.2
Total	0.3
Input non-circularity rate (INCr)	32.9
Output non-circularity rate (ONCr)	51.6

The input and output socio-economic cycling rates, as well as non-circularity rates, clearly indicate low material circularity and a high dependence on fossil fuels for energy needs in The Bahamas. With 2,350 kt/yr of PM utilized in the island system, and recycling of only 7 kt/yr, the total ISCr in 2018 results in 0.2%. OSCr shows a slightly higher average value at 0.3%. The analysis shows that biomass is the material category with the highest ISCr at 1.1% and OSCr at 1.4%, as green (biomass) waste is the predominant material recycled (6.4 kt/yr). In 2018, there was no reported recycling of fossil products or minerals. The input non-circularity rate (INCr) indicates that 33% of the total mass of PM is comprised of fossil energy carriers. Similarly, the output non-circularity rate (ONCr) indicates that 52% of the total mass of IntOut is comprised of fossil energy carriers. In the Bahamian context, major obstacles to increase circularity include: the low levels of recycled materials, the physical growth of the economy as in-use stocks (NAS), and the relatively high shares of fossil energy carriers in PM.

4.5 Discussion

4.5.1 Resource-use patterns in The Bahamas compared to other island territories

Overall, island territories exhibit a limited and unequal distribution of natural resource-bases, growing trends in resource demand, rapid urbanization, heavy dependence on imports that causes elevated costs of basic supplies, poor connectivity and high costs of crossing open sea, which function as stressors over the supply of essential resources. Together with other complex social, economic, structural and climate pressures that further exacerbate their exposure to shocks (UN-OHRLLS, 2022), the overall resource security and sustainability of island territories are under threat. Proper management and monitoring of the physical characteristics of national economies (e.g., through MFA and circularity indicators) are key to foster their sustainable and resilient development. By comparing island territories (e.g., based on their characteristics of production, trade, and resource-use patterns), one gains a better understanding of varying patterns of metabolic profiles, embedded socio-metabolic risks, and opportunities for mitigating those risks by reconfiguring trajectories of resource-use within their own contexts.

Table 9 shows a comparison between different input, output, and use indicators for various islands and regions around the world, normalized per-capita to enable comparison. These island cases exhibit varying combinations of resource extraction, waste, trade, and use. Characteristics such as the main economic activity, infrastructure (e.g., fishing fleet, harbors, mines, pipes for fuels transportation), and natural resource-bases influence their metabolic profiles. The Bahamas can be viewed as a tourism-driven economy with a limited resource base and low manufacturing capacity. With no fossil fuel reserves and limited renewable-energy generation capacity, the energy carriers extracted from the domestic environment comprise low amounts of biomass fuelwood. This makes the country almost 100% dependent on imports of fuels for its energy needs. In comparison, Trinidad & Tobago—an industrial Caribbean country with an adequate resource base and infrastructure dedicated to fossil fuel extraction and processing—is not dependent on fuel imports.

Table 9 - Comparison of per-capita MFA indicators, numbers in [tonnes/cap/yr].

Island territory	**Year**	**DE**	**Import**	**Export**	**DMI**	**DMC**	**Main DMC contributor**	**Sources**
The Bahamas	2018	5.5	3.9	3.3	9.4	6.1	Fossil fuel, Non-metallic minerals	Present study
Samothraki	2018	13.8	5.0	2.3	18.8	16.5	Biomass	Noll et al. (2021)
Iceland	2008	14	15.1	6.1	29.1	23	Biomass, Non-metallic minerals	Krausmann et al. (2014)
Trinket Island	2000	N.D.	N.D.	2.4	6.2	3.8	Biomass, Non-metallic minerals	Singh et al. (2001)
Trinidad & Tobago	2008	34.7	8.8	26.2	17.3	17.4	Fossil fuels	Krausmann et al. (2014)
Oahu Hawaii	2005	3.7	16.6	6.7	20.3	13.6	Fossil fuels	Eckelman & Chertow (2009)
New Caledonia	2016	N.D.	10.6	N.D.	N.D.	29.3	Non-metallic minerals	Bahers et al. (2020)
Santa Cruz (Galapagos)	2012	16.3	4.4	0.1	20.7	20.8	Non-metallic minerals	Cecchin (2017)
Japan	2015	4.6	6.13	1.4	10.7	9.3	Non-metallic minerals	Tanikawa et al. (2021)
Global average	2019	12.5	1.9	1.8	14.4	12.4	Non-metallic minerals	UNEP & IRP (2022)
Europe average	2019	16.4	7.9	5.8	24.3	18.5	Non-metallic minerals	UNEP & IRP (2022)
LAC average	2019	16.9	1.2	2.3	18.1	15.8	Biomass	UNEP & IRP (2022)

Note: Domestic Extraction (DE). Direct Material Input (DMI). Domestic Material Consumption (DMC). No Data (N.D.). Latin America and the Caribbean (LAC)

The Bahamas' DE mainly comprises non-metallic minerals (salt, sand/gravel). Virtually all salt extraction (around 850 kt/yr) is exported, while close to 100% of sand and gravel extraction (360 kt/yr) is directed towards building and maintaining building stocks. Likewise, the islands of New Caledonia and Santa Cruz also exhibit a DE focused on minerals; however, slight differences are seen in the end uses in these islands. New Caledonia is one of the largest nickel producers in the world, as such, the country is a supply-base for other economies, with export flows of this resource (Bahers et al., 2020). On the other hand, Santa Cruz extracts large amounts of volcanic rocks that end up being used for the local construction of stocks and concrete block production (Cecchin, 2017).

In The Bahamas, although the exclusive economic zone (EEZ) of the country is many times larger than its land area (45:1 ratio) (Sea Around Us, 2016), marine biomass DE represents less than 1% of total DE and just around 5% of total biomass DE. With a fishing fleet characterized as small scale (FAO & Government of The Bahamas, 2016) and dedicated to catching a few targeted species, The Bahamas' exploitation of marine resources is low compared to other islands. In comparison, Iceland, with a lower EEZ-to-land area ratio (7:1), has a marine biomass DE of 30% of total DE and 60% of total biomass DE (Krausmann et al., 2014). The development of its fishing fleet infrastructure has enabled Iceland to exploit that particular resource.

A similarity seen across many islands is the high masses of waste generation, especially in Caribbean SIDS. Most of this ends up in (uncontrolled) disposal sites where it takes up space and generates greenhouse gases from decomposing (biomass), which contributes to global warming and produces residues that may pollute underground water, among other issues. The Bahamas shows higher levels of MSW generation (1.85 kg/cap/day) than the Global (0.74 kg/cap/day) and LAC region (0.99 kg/cap/day) averages during 2016, and is one of the highest waste generators among the Caribbean SIDS (Kaza et al., 2018). A common characteristic of island territories is the high share of organic waste in MSW (Kaza et al., 2018), the lack of sanitary landfills to properly dispose of waste (IDB, 2016a, p. 23), and the low masses of waste materials recycled (Mohee et al., 2015). This could be associated with limited policies and funding to promote waste management, a lack of understanding of material waste composition, limited studies on waste characterization and recycling opportunities, and limited infrastructure to process waste that arrives at disposal sites (Global Environment Facility, 2019; Mohee et al., 2015). Although the government, environmental activists, local NGOs, and other initiatives have made efforts to curb waste and pollution, the total masses of waste generation are still relatively high.

4.5.2 Do current patterns of resource use in The Bahamas constitute socio-metabolic risk?

As the analysis of indicators shows, the case of The Bahamas displays specific patterns of resource use that might place the country at metabolic risks. By improving the understanding of such risks and their aftereffects, the island system can continue to provide critical societal services consistently and effectively in the long run. Table 10 briefly shows the condition of the case study, emphasizing the potential risks associated with the levels of inflows and outflows and resource use as well as observed evidence of those risks, some of the potential cascading effects and suggested mitigation strategies.

Table 10 - Metabolic Patterns, Associated Risks, the Current Situation in The Bahamas, Potential Cascading Effects and Mitigation Strategies.

Metabolic pattern	**Metabolic risks**	**Observed evidence**	**Cascading effects**	**Potential risk mitigation strategies**
(A) High fuel imports and consumption	Energy price fluctuations	Fuel prices have been steadily increasing over the past years.	Impact on cost of electricity and other goods/services; continued emissions of greenhouse gases contribute to climate change hazards.	Increase energy efficiency and self-sufficiency through energy generation via clean technologies (wind, solar, ocean, etc.).
	Oil spills and runoffs	Equinor oil spill (5 million gallons spilled over Grand Bahama's pine forest after Hurricane Dorian in 2019) (Save the Bays & Waterkeeper Alliance, 2019).	Damage to pine forest and wetland ecosystems; water table pollution; power generation shortages; specialized labor required to clean up and restart plants.	Strengthen oil spill prevention, control, and mitigation programs. Hasten the transition to cleaner energy technologies.
(B) High extraction of minerals	Erosion, loss of coastal shoreline, impacts on local ecosystems	Past mining of sand at Ocean Cay left the island in a poor state, with extensive damage to the ecosystem.	Loss of habitat for species offshore and onshore; change in water flows; economic losses from tourism abandonment; economic losses from fisheries; loss of ecosystem services such as protection from extreme sea levels, leading to greater exposure to climate change hazards.	Design, apply, and evaluate management strategies aimed at the sustainable exploitation and utilization of resources. Application of restoration programs for local ecosystems (e.g.., through nature-based solutions).
(C) High utilization of materials for construction	Higher maintenance requirements	Nassau and Freeport contain more than 80% of the population, and Nassau's urban growth has reached the extent of the island.	Increase in use of resources from building construction, maintenance, and operation; noise, traffic, pedestrian congestion; hotspots of pollution; health issues.	Optimize development planning and existing infrastructure by redesigning and upgrading stocks through the adoption of alternative construction materials (e.g., ecofriendly materials).
	Higher exposure to natural hazards in areas prone to erosion and flooding	Infrastructure at risk from the negative effects of climate change (e.g., flooding and storms).	Interruption of critical services; costly debts from the reconstruction of infrastructure (e.g., roads, ports).	Implement strategies that combine the use of natural, vegetated, hard, and engineered coastal defense structures that can reduce the need for additional materials, lower overall infrastructure expenditure and increase resilience.
	Increase in logistics complexity	The archipelagic nature of The Bahamas and its dense urban centers make it difficult to transport resources in a timely and efficient manner.	Untimely deliveries causing services/businesses to suffer; potential loss of lives when facing external shocks; food insecurity.	Identifying and mapping critical buildings, transport nodes, and networks to prevent and adapt to potential logistics issues.
(D) Undiversified utilization of marine resources	Overexploitation of targeted species	Spiny lobster/queen conch harvest has suffered from unsustainable fishing practices.	Threats to the balance of fragile ecosystems, food security, and local livelihoods.	Enforce a monitoring framework to collect and maintain data on marine resources in the country, including research on potentials for sustainable exploitation of marine species.
	Increased dependency on	No ocean/offshore (wind/solar/ocean	Continued risk of environmental pollution and greenhouse	Further support the national energy policy to promote and apply a

	non-renewable energy sources	currents/other) renewable energy capacity installed.	emissions; increased foreign dependency.	comprehensive program of efficiency improvement and energy diversification in the country.
(E) High masses of waste	Uncontrolled management, no space for proper processing, landfill leachate, and fires	There have been recurring landfill fires over the past years (Bahamas Information Services, 2017; PAHO, 2017); currently, only 3 sanitary landfills (main islands) and 6 open non-sanitary landfills and dumpsites exist.	Pollution of the water table, gas emissions, health impacts in the surrounding community, impacts in the tourism industry.	Implement and strengthen solid waste management plans and strategies (technical and operational), as well as proper waste disposal infrastructure and maintenance. Waste characterization studies may be an opportunity to explore waste-to-energy alternatives.

Overall, fossil fuel prices have been steadily increasing over the past years, directly impacting the costs of goods and services (see Table 10, number (A)). In addition, the growing population, shifting consumption patterns, and increasing urbanization, among others, have escalated the demand for mineral resources mainly used for construction (see Table 10, number (B) and (C)). The accumulation of these materials for building stocks, in turn, influences the need for more resources for their maintenance. While these mineral resources are indeed necessary, extractive practices could be environmentally damaging to sensitive ecosystems. Coupled to the country's socio-economic and physical exposure to disasters, future affectations on infrastructure and critical services represent an existential threat (UNISDR, 2015).

Although the Bahamian exclusive economic zone territory covers a vast ocean area, there is an undiversified utilization of marine resources (see Table 10, number (D)). This untapped potential for exploitation, however, should consider the predicted consequences of using or not using the resource. Diversification of fish stocks DE (e.g., through aquaculture, or emerging fisheries such as the deep-sea ones) could reduce the pressure on currently targeted species to significantly improve the overall fisheries stocks' health. Additionally, this could alleviate imports dependency and increase the competitiveness of the country in the international scenario. Similarly, investments in ocean-based renewable energies (e.g., near-shore and off-shore wind turbines, ocean thermal energy conversion) can improve the energy self-sufficiency of the country, thus reducing foreign dependency on fossil fuels.

The country generates high masses of waste and has minimal levels of circularity (see Table 10, number (E)). The most pressing issue is the disposal of waste, which continues to be dumped in open or uncontrolled dumpsites as opposed to properly designed sanitary landfills. Combined with insufficient infrastructure and gaps in technical and operational procedures, the country is exposed to health and public safety risks such as recurrent fires and environmental litter, which also negatively impact the tourism industry.

4.5.3 How can The Bahamas reduce its metabolic risks?

Given the specific metabolic profile of The Bahamas, a holistic resource management strategy and nature-based solutions (NbS)—which consider the trade-offs and synergies between different resource-use patterns—are critical when exploring directions for reducing risks (Failler, 2020; Gerritsen et al., 2021; Wüstemann et al., 2017). The current energy crisis triggered by the war in Ukraine at the beginning of 2022 and interruption of global supply chains since the beginning of the Covid 19 pandemic lays bare metabolic risks associated with import dependencies, especially for SIDS. Strategies should include features and monitoring approaches that fully incorporate and maximize the local capacity for resilience and mitigation at both the environmental and socio-economic levels.

Evidence suggests that The Bahamas has embraced an energy strategy still dependent on fossil fuels (see Table 10, number (A)) that exposes SMRs and that could quickly become a metabolic trap, thus potentially leading to socio-metabolic collapse. Moreover, like many island nations, The Bahamas has limited renewable energy generation and exhibits large (fossil-based) energy consumption, with elevated energy losses, and high electricity tariffs (NREL, 2015f) that steers the system into an unsustainable metabolic state. It is imperative to find ways to accelerate the energy transition and increase energy efficiency in the country. The Bahamas shows excellent conditions to benefit from a combination of modern and efficient ocean-based renewable-energy technologies due to the country's elevated costs of fossil fuels, its size, and the existing potential of renewable energy. Estimations from the National Renewable Energy Laboratory set the potentials of wind and solar renewable energies at 200 MW and 60 MW, respectively (NREL, 2015f). Given the current generation capacity of around 536 MW based on fossil fuels (NREL, 2015f), renewable energy could reduce the dependency on imported energy carriers by almost 50%, thus reducing the associated metabolic risks and providing direct economic advantages.

The harvesting and trade of marine biomass resources produced by fisheries and aquaculture sectors can greatly contribute to the current global and local demand for food, nutrition, and protein, as well as for research and development in bioprospecting. As the country imports most of their protein requirements in the form of animal meat, dairy products, and eggs (FAO, 2021a), increased use of domestic marine protein could greatly reduce this import dependency. Furthermore, maritime tourism and transportation can contribute to position the country in a more favorable place for commerce and trade in and around the oceans, as well as contributing to other economic activities and environments, such as coastal protection and resilient growth, with the potential for increasing local ecosystem rehabilitation and conservation (The World Bank, 2017).

Infrastructure development requires construction materials. Non-metallic minerals (sand/gravel) are key materials utilized for this expansion, particularly for the construction of buildings and roads. However, commercial exploitation of these resources may lead to severe environmental and economic issues such as erosion, flooding, and coastal hazards, among others (see Table 10, number (B) and (C)). Options to reduce these potential risks include optimizing or even reducing existing infrastructure by redesigning and upgrading stocks through the adoption of alternative, sustainable construction materials. By incorporating eco-friendly materials (e.g., bamboo), The Bahamas could transform its built environment, facilitate material circularity, create green jobs, improve tourism amenities, and overall health and quality of life through reduced emissions. In addition, the repurposing of waste materials could reduce overall raw material consumption and waste pollution streams (see Table 10, number (E)). as in the case of the utilization of plastic waste in the roads on the Honduras island of Utila in the Caribbean (Pelliccia, 2018). In parallel, studies on current rates of production and consumption of minerals with mapping of mining areas are critical to correctly evaluate the environmental and economic impacts. With this, it would be possible to design management strategies aimed at the sustainable exploitation and utilization of resources.

For The Bahamas, the adoption of a circular economy can be viewed as an opportunity to enhance resource efficiency, reduce waste, strengthen climate change adaptation, and build system's resilience. Reconfiguring resource-use patterns can also be a crucial strategy to minimize and counter SMRs. The more resources are circular or localized, the less dependence on external economies for imports, which could allow for access to goods and services when needed. Also, the less dependence on external economies, the less magnitude of SMRs and more resilience to shocks (e.g., in case of a breakdown of the supply chain), thus, increasing resource security. In parallel, circular economy strategies could reduce and prevent damage to sensitive ecosystems by reducing the demand for raw materials, which increases the health of essential ecosystems that improve climate adaptation and increases the resilience of infrastructure (e.g., mangroves protecting the built environment against flooding, and serving as nursery habitat for fish, etc.).

One of the first steps to achieve this transition should be focused on understanding the flows of materials throughout the economy. Based on this Chapter's results, as waste streams in The Bahamas are an issue of concern (see Table 10, number (E)), a potential "high-return, low-risk" item could be the proper management of this outflow. The investment in infrastructure and proper management of supply chains at the production, storage, operation, and distribution levels is required to manage this (Ewing-Chow, 2019b). Moreover, the combination of these strategies together with the application of nature-based solutions (which are actions that simultaneously enhance ecosystem resilience and address multiple societal challenges), could be an excellent opportunity to minimize waste and related SMRs while offering cost-effective approaches & synergistic co-benefits. The organic fraction of the waste stream, which represents around half of the total MSW in The Bahamas, could be used as input to produce an array of safe and valuable products such as fertilizer (green waste compost), soil substrate, energy carrier (biogas), and more. Also, the management of plastic waste and the adoption of alternative materials (e.g., for food packaging and containers) are needed to complement a circular economy and reduce resource depletion. Nature-based solutions can also be helpful in this regard, such as the exploitation of invasive brown seaweed to elaborate biodegradable bioplastic as an alternative to traditional plastic packaging and containers (Mohammed et al., 2023).

Highly dense urban centers in low-lying flatlands with close proximity to the coastline may cause an array of environmental, health, and infrastructure issues, including inland flooding, erosion, coastal hazards, and pollution that are increasing with strengthening climate change. Conventional approaches to combat these threats include hard engineered structures such as sea walls and breakwaters. However, these man-made structures further perpetuate the dependency on non-metallic mineral imports for their construction (see Table 10, number (B) and (C)). There is the need to implement strategies that combine the use of natural, vegetated, hard, and engineered coastal defense structures that can reduce the need for additional materials, lower overall infrastructure expenditure and increase resilience (Silver et al., 2019; van Zelst et al., 2021). One specific example in The Bahamas is the recent investment in the exploration of nature-based solutions to support climate-resilient tourism and infrastructure development in San Salvador, while at the same time protecting ecosystems and cultural heritage sites (IDB, 2016b). Additionally, one can find investment in road upgrades throughout the country with targeted mangrove restoration to enhance resilience to coastal flooding and erosion, while at the same time enhancing road access for vulnerable coastal communities (Oliver et al., 2021).

Other nature-based solutions that can be utilized as coastal defense structures (e.g., coastal wetlands, coral reefs, salt marshes, etc.) have the potential to help reduce metabolic risk by means of reducing wave heights and can be several times cheaper than artificial submerged breakwaters (Narayan et al., 2016). These can also serve as a nursery habitat for fish, a home for other marine species, and a natural filter for pollutants (S. Y. Lee et al., 2014). Coastal wetlands have the potential to grow with climate change-driven sea level rise and expand in area. However, this is only possible if enough inland accommodation space is given to coastal wetlands (e.g., through elevation management of the coastal topography, or through a process of "managed retreat" in which wetlands can form as inundation occurs) and these areas are protected such as with upland nature reserves (Bridges et al., 2021; Hein et al., 2021; Schuerch et al., 2018; Zhu et al., 2010). However, these approaches must be considered cautiously so they do not heighten the existing dependency on material imports and do not add to the current coastal squeeze effect.

The dependency of The Bahamas on imported food and fuel could possibly be lessened with introduction of forest management adopted to dry-land forests. Fall et al. (2021) conducted pollen analysis of the Bahama's sediment record and found that the current pine forests are not native but were introduced about 1,000 years ago by Amerindian settlers. The original forest cover consisted of local hardwood and palm species that were more hurricane resilient than the current pine species. Most of The Bahamas is covered by a tropical savannah climate and characterized by karst geology, suggesting that forest management approaches specialized to semi-arid regions would be required. These approaches might serve to produce a limited supply of local fuel wood, regenerate soil, and reduce soil erosion. Acknowledging typical soil moisture and nutrient limitations of karst ecosystems (S. Zhang et al., 2022), opportunities could be explored to combine native tree species reforestation with agro-forestry approaches to include modest pastures for small livestock or intercropping of suitable crop species (Bayala et al., 2022; Keesstra et al., 2018).

4.6 Summary of findings on the significance of resource-use patterns and socio-metabolic risks to build resilience in small islands

This Chapter presents the first study that applies an ew-MFA mass-balance to assess the biophysical economy of a small island nation to identify metabolic risks. The study has characterized the Bahamas' distinctive metabolic profile and identified associated risks through assessment of its socioeconomic metabolism in regard to resource use, waste generation and material circularity. It offers insights on the potentials that reconfiguring the flows of material input, output, and circularity may offer to articulate adaptation strategies aimed at bringing functionality, stability, and resource security, while minimizing metabolic risks and build resilience in the system. In addition, the results of this Chapter clearly demonstrates that resource management is integral to properly managing systemic risks, especially in SIDS. Inadequate resource management could adversely impact primary economic sectors (e.g., tourism), resource self-sufficiency, resilience, human and ecosystems health, and quality of life, among others.

This Chapter provides insights into the potentials of using the ew-MFA framework to identify socio-metabolic risks. Mitigating socio-metabolic risk is crucial for small islands to withstand climate impacts and avoid cascading dysfunction of environmental, economic, and social systems. Simultaneously, it enables a much-needed estimation of the physical dimension of the economy in terms of flows of materials in the island context. As most of the data sources utilized in this study are freely available, the proposed framework can be easily replicated in many other territories with relatively low time and resource investments, especially for other SIDS and developing countries. However, care must be taken to ensure the quality and completeness of the data to reduce uncertainties as the particularities of data collection for each case study may represent a challenge. The ew-MFA mass-balance analysis thus calls for improvements in overall data quality, including the development of proper input and output statistics, in addition to waste composition and materials cycling data.

Moreover, as the ew-MFA and circularity indicators are more focused on the monitoring of the physical dimension of the economy, there is the need to expand the analysis to other components of the economy like the social and cultural dimensions (e.g., governance, consumer habits and preferences). These play a key role in shaping the resource-use dynamics and in the adoption of strategies that could minimize socio-metabolic risks. These improvements would allow for a more holistic understanding of not only metabolic scales, rates of circularity and end-uses of materials in the system, but also of the cultural and institutional drivers and barriers influencing over the resource-use dynamics. Future work should include robust strategies that analyze, identify and quantify the social, economic and environmental trade-offs and synergies of reconfiguring resource-use patterns. This would consequently lay the foundation for a better understanding and prioritization of potential metabolic risks and cascading effects to build resource security and system resilience.

SIDS must continue exploring and developing an enabling environment to progress towards greater resource security and resilience. For The Bahamas, an untapped potential exists in the ocean that is “at hand’s reach” (CARICOM, 2017; CCREEE, 2019; Failler, 2020; IRENA, 2016). Currently, efforts dedicated to truly broadening these possibilities have focused on outlining and pursuing a development pathway aligned with the blue economy, which is inclusive of the assets, goods, and services that the ocean may offer, and embedded with the concepts of the circular economy (Bahamas Development Bank, 2018; Government of The Bahamas, 2016b; IDB Group, 2021). However, these efforts have just recently been implemented. Moreover, climate change impacts the already insufficient ocean infrastructure (Government of The Bahamas, 2021; Kemp, 2019), while challenges such as governance and monitoring deficiencies still remain (Bethel et al., 2021; IDB, 2022b; Sustainable Islands Platform, 2019). Notwithstanding, designing a strategy through a blue economy vision could thereby assist in minimizing or reducing metabolic risks and building resilience by employing reconfigured resource-use patterns.

Chapter 5: The role of critical infrastructure on sustainability and resilience in small islands[3]

5.1 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 including sea-level rise (SLR). This is especially significant for the most disaster-prone countries in the world: Small Island Developing States (SIDS). 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, the study conducted a spatially explicit Material Stock Analysis (MSA) for The Bahamas for 2021, where it was included Buildings and Transport MS. 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-meter SLR scenarios, ~4 mt, ~6 mt and ~9 mt of current MS will be exposed, with Transport MS at greatest risk, with over ~80% of total exposure in each scenario. The findings of this Chapter highlight the critical role that key MS plays in sustainability and resilience, contributing to emphasize effective development planning and climate change adaptation strategies, and to explore the use of OSM data for studying these objectives.

5.2 Introduction

Between 1970 and 2010, global material extraction of construction materials has shown a five-fold increase, far exceeding population growth, which has led to a considerable increase in the rate of 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

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[3] The contents of this section of the Chapter have been incorporated within a paper that has been submitted for publication. 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”. Submitted to the *Journal of Industrial Ecology*. Reviews submitted: December 17, 2022. Minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

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 region, growth in infrastructure is of special significance, considering the impacts of sea-level rise and extreme events, which are increasing both in frequency and intensity (CRED & UNISDR, 2018; IPCC, 2022a). 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). In the Caribbean Small Island Developing States (SIDS), population has increased by 15% since 2000, from around 6.5 million to 7.4 million in 2020 (The World Bank, 2022i), while average urban development reached 50% in 2020 (The World Bank, 2022l). According to the WorldRiskReport, 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, which have affected 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), and Nasir et al. (2021)). Most recently, the combination of geospatial data and socioeconomic data with statistics on material stocks (MS) (e.g., Heeren & Hellweg, (2019); Tanikawa et al., (2015)) has advanced our understanding of MS dynamics. However, only few studies on MS 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), while fewer have had small islands as their area of study, particularly with the explicit aim of studying risks from disasters (e.g., of sea-level rise (SLR)) (Bradshaw et al., 2020; Lingfei, 2022; Merschroth et al., 2020; Symmes et al., 2019). SLR threatens vital infrastructure, settlements, and facilities that support the livelihood of island communities, especially those of low-lying territories (The World Bank, 2017). Moreover, information on MS patterns and drivers of risks in these highly dynamic coastal zones is essential for current and future development. Thus, island governments increasingly realize the importance of strengthening the resilience of their infrastructure and communities, pushing for effective development planning strategies as measures to reduce systemic risks and enhance resilience to climate variability and change. These risks should not be only understood only through the impacts of SLR on infrastructure stocks, but also on the amplification of risks due to the compounding effects of multiple hazards happening simultaneously or sequentially that trigger cascade effects and that affect other components of the system, which puts development needs in jeopardy (Franzke et al., 2022; Klose et al., 2021).

This Chapter's study aims to contribute to the literature on stock dynamics through an economy-wide Geographical Information System (GIS) bottom-up Material Stock Accounting (MSA) analysis for The Bahamas for 2021. It focuses on estimating current and future MS and their exposure to SLR, and analyzing the compound and cascade effects that impact on other system's components, such as in the built and natural environment, society and the economy. Moreover, this study expands on the MSA analysis and brings 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. Furthermore, this study will inform about potential directions of future resilience-development strategies in the country. Specifically, This Chapter focuses on the MS of: a) buildings, and b) transport infrastructure. This investigation is guided by the following questions: What is the current composition of MS in The Bahamas and where are they located? What is the expected evolution of MS and future material requirements? How do SLR scenarios impact current MS and future development? The analysis draws on OSM data to compensate for the lack of fundamental information from formal sources about buildings and infrastructure stock. Challenges and potentials of this approach were also discussed.

5.3 Case-study: 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 an Exclusive Economic Zone of around 650,000 km^2 (Soobramanien & Worrall, 2017) and a total internal land area of around 14,000 km^2 (The Bahamas Protected Area Fund, 2020) of which 80% is less than 10 meters above sea level (Reguero et al., 2015). The population is approximately 400,000 as of 2021 (Worldometer, 2022a), with 70% of it living on two islands: New Providence and Grand Bahama (Government of The Bahamas, 2012). Tourism and tourism-driven activities represent approximately 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 (Silver et al., 2019; M. C. Simpson et al., 2010). The country, which was impacted by 14 storms between 2001 and 2019 (EM-DAT & CRED, 2022), is particularly vulnerable to the shocks of recurrent natural disasters. These climate change-related threats put at risk significant portions of the built and natural environment, and economy of The Bahamas (IDB, 2022c; 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 (Bello, Fonted de Meira, 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.

5.4 Methodology

To analyze current buildings and transport stocks, future material requirements, and potential impacts of SLR, a GIS-based MSA for 2021 was conducted. The study area was the political boundary of The Bahamas. Estimations were derived using the ArcGIS Pro 2.8.3 software. Section 6.4.1 provides further details on datasets limitations. Appendix C provides underlying data about the approach taken to quantify current and future material stocks in The Bahamas for the year 2021. Appendix C also contains additional information about steps to account for the impacts of sea-level rise on material stocks. It also provides further data on figures and tables for Chapter 5.

5.4.1 Stocks of buildings

The general approach in estimating 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 use-type, 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, which were sourced from OpenStreetMap (OSM) and extracted through the Humanitarian Data Exchange project (HOTOSM) (Humanitarian OpenStreetMap Team, 2021a), was used as a base data.

The existing building footprints were classified into five main use-types: 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 use-types. Satellite imagery was interpreted and associated to the remaining uncertain building footprints with nearby known buildings based on size and layout, and extra information within the OSM shapefile layer. This allowed to allocate distinct MI values (in kg/m^2) for these main use-types. 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$_{(b)}$.

Equation 1

$$GFA_{(b)} = Building\ footprint\ area_{(b)} \times Number\ of\ floor\ stories_{(b)}$$

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 *"$MI_{(m)}$"*.

Equation 2

$$MS_{(b,m)} = GFA_{(b)} \times MI_{(m)}$$

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, the census of population and housing (Government of The Bahamas, 2012), as well as the household expenditure survey (Government of The Bahamas, 2016a) were explored. Previous publications with information on the building typologies of other Caribbean SIDS, namely Grenada (Symmes et al., 2019) and Antigua & Barbuda (Bradshaw et al., 2020) were also consulted.

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 (such as 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 & 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. Besides, 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 & 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 a structure of concrete blocks (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 in use as well, but with lower numbers (ECLAC, 2020). Considering that The Bahamas' building typologies share more similarities with Grenada's buildings (concrete-dominant) than with Antigua & Barbuda (timber-dominant), the study utilized the MIs described in Symmes et al. (2019). See Table 11 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:

Equation 3

$$MS_{total} = \sum MS_{(b,m)} = MS\_Aggregate_{(b,m)} + MS\_Timber_{(b,m)} + MS\_Concrete_{(b,m)} + MS\_Steel_{(b,m)}$$

To calculate total MS per building use-type, Equation 3 is applied for each of the five use-type categories (see Table 12).

5.4.2 Stocks of transport

For transport-related stocks, the share of paved roads in the road network, airports (buildings and runways), and main seaports (buildings and cargo platforms of larger seaports) were considered. During the transport stocks classification process, three GIS shapefile layers in parallel were consulted. The first shapefile was the same containing most of the building footprints of The Bahamas from the ones corresponding to seaports and airports were filtered. 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 roads. The paved roads were further classified into five main use-types 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).

The material intensities for roads were obtained from the Design and Construction Guidelines for roads in The Bahamas, which contains specific designs for paved roads. The main materials for the paved carriageway were considered as asphalt of 4 cm thickness, with base layer of base material and 20 cm thickness, with sidewalks made of concrete (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), an assumption was made 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 layer of asphalt of 10 cm thickness, a second layer of concrete of 12 cm thickness, and a base material layer of 25 cm thickness (U.S. Department of Transportation, 2016, pp. 3–17).

The Building Code of The Bahamas does not contain specific design specifications for seaports cargo platforms. As these would be under heavy loads like those in airport runways, an assumption was made that the Airport Pavement Design and Evaluation guidelines would also apply to the seaport's cargo platforms. As such, the main materials for the platforms consisted of a surface layer of 15 cm thick concrete, and a 40 cm thick layer of base material (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 Table 11 with MIs for buildings and transport stocks.

Material Stocks "*MS*" were calculated for each transport element type "t" and for each main material categories "m" by multiplying the transport type total gross floor area or total length "$TX_{(t)}$" by its corresponding "$MI_{(m)}$".

Equation 4

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

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

Equation 5

$$MS_{total} = \sum MS_{(t,m)} = MS\_Aggregate_{(t,m)} + MS\_Timber_{(t,m)} + MS\_Concrete_{(t,m)} + MS\_Steel_{(t,m)} + MS\_Asphalt_{(t,m)} + MS\_Base\_Material_{(t,m)}$$

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 12).

Table 11 - Material Intensities allocation for buildings and transport stocks. Units as indicated.

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	1,645	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	1,125	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	1,645	325	
Transport	**Concrete**	**Asphalt**	**Base material**		
Roadways *(kg/m)*					
Major subdivision roadway	598	667	2,453		
Minor subdivision roadway	0	552	2,050		
Local street	0	552	2,050		
Airport runways (kg/m^2)	305	234	427		
Seaports platforms (kg/m^2)	366	0	640		

Sources: Government of The Bahamas, (2004); Symmes et al., (2019); U.S. Department of Transportation, (2016). 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 MIs, affects the ability to reduce uncertainties on MS 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.*

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

The potential near-future material requirements for buildings and roads was estimated grounded on two assumptions. First, 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 indicating where development will likely happen. The second assumption corresponds to future roads' MS. The study also assumes that currently unpaved roads will be upgraded to a paved roadway type in the future, thus changing their material intensities and subsequently their material stocks (Appendix 3 provides further details on this methodology).

Future buildings - As first step, the current density of both buildings and roads for the whole country were examined. 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. As seen in Figure 9 (e.g., east and west sides of New Providence), specific zones within the island present varying levels of development for both buildings and roads. For different locations "i", it was estimated the ratio "$RA_{(i)}$" of building gross floor area "$GFA_{(i)}$" vs. road length "$RL_{(i)}$" as follows:

Equation 6

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

A test-run was conducted for the capital island of New Providence (see Figure 9). This test showed us that, for this island, $RA_{(i)}$ ranges from 9.6 to 11.4 for highly dense areas, and from 4.8 to 5.8 for less-dense areas.

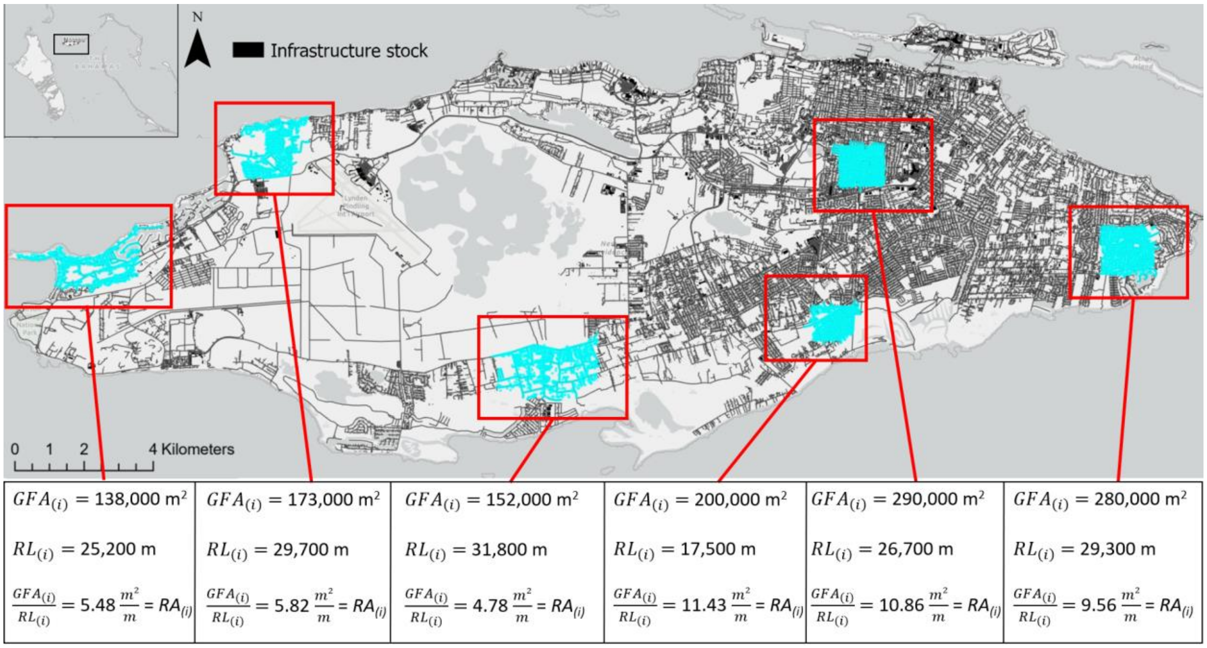


Figure 9 - Ratios RA(i) of building gross floor area GFA(i) per road length RL(i) for different highlighted zones in New Providence in 2021. Source: Humanitarian OpenStreetMap Team, (2021a, 2021b)

To account for country-wide variations, the study 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. The study 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.

Equation 7

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

Average MI was based on the overall MIs for each building use-type and current shares of building MS use-types. The results seen in Table 13 are based on a conservative estimate of only 5% of total future building MS.

Future roads – As first step, the study selected the roadways that will potentially become paved in the future. Within the OSM roads shapefile layer, the study assumed that these include the roads with "path" and "unclassified" tags. The study accommodated these under the "minor subdivision road/local street" use-type. Additionally, through analyzing the roads network shapefile and directly observing satellite imagery (Google Earth Pro®, 2021), the study included those areas containing "track" roads that display a distinct spatial arrangement characteristic of the preliminary works for future urban development. 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 *"$MI_{(m)}$"*.

Equation 8

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

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

Equation 9

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

5.4.4 Sea-level rise scenarios

These simulations were based on assessments of 1-meter (Intermediate-High projection) and 2-meter (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 meters presents a more critical situation, where SLR continues to rise past the year 2100. For the simulations, the study utilized a set of digital elevation model (DEM) data obtained from the *U.S. Geological Survey* (USGS, 2022). Polygon shapefile layers were then created by filtering elevations from the DEM. The impacts of SLR were estimated by overlaying the SLR polygons on building and road stock data and summarizing the MS that would be exposed under each scenario (see Figure 10 and Table 14).

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). Together with the generated SLR polygons, and the current spatial distribution of buildings and transport stocks, the study expanded on some potential effects of SLR over current stock and future development.

5.5 Results

5.5.1 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 around 57% and 43% of the totals, with 43.1 mt or 108.6 t/cap, and 32.8 mt or 82.6 t/cap respectively. Table 12 summarizes the MS findings.

Table 12 - Synthesis table showing the total existing material stocks, by infrastructure element and main construction material in The Bahamas in 2021. Total MS: Units in mt. Total MS per capita: Units in t/cap.

Building element	**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 element								
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**

Note: Numbers may not add-up due to rounding. N.A. = Not Applicable

Residential buildings account for 67% of total building MS, at 28.7 mt or 72.3 t/cap. Commercial use-type account for around 27% of total building MS, at 11.5 mt or 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 5,900 km of paved roads divided between major roads subdivision (approximately 820 km) and minor roads subdivisions (around 5,080 km). Total paved road network MS was estimated at around 16.2 mt or 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. The study identified more than 60 major, regional, and small airports amounting to a total MS of about 14 mt or 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. Moreover, buildings associated with airports were estimated at 0.6 mt.

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

The concentration and distribution of MS between building and transport are spatially uneven. Infrastructure is located 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 13). Further, most MS and commercial activities are located in urban centers, especially in the capital city of Nassau in New Providence.

5.5.2 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 13). West Grand Bahama and New Providence both have similar road lengths, but there is a great difference in their total building GFA (4 km^2 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 2,000 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 road infrastructure, results show that additions to road stocks amount to around 4.5 mt of new material and 2,000 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 13), which are currently some of the main urban centers in the country. The analysis revealed that only few land-use zoning or planning for many of the major islands and family islands have been developed. Nonetheless, the results of the MS analysis managed to produce similar results on future development zoning (see Appendix 3, Figure C - 13) as the ones proposed under the Andros Master Plan and Sustainable Nassau Plan (Government of The Bahamas, 2017, pp. 15, 16, 17; IDB, 2018, pp. 42, 43).

Table 13 - Estimations of current (year 2021) and future building MS for each district in The Bahamas

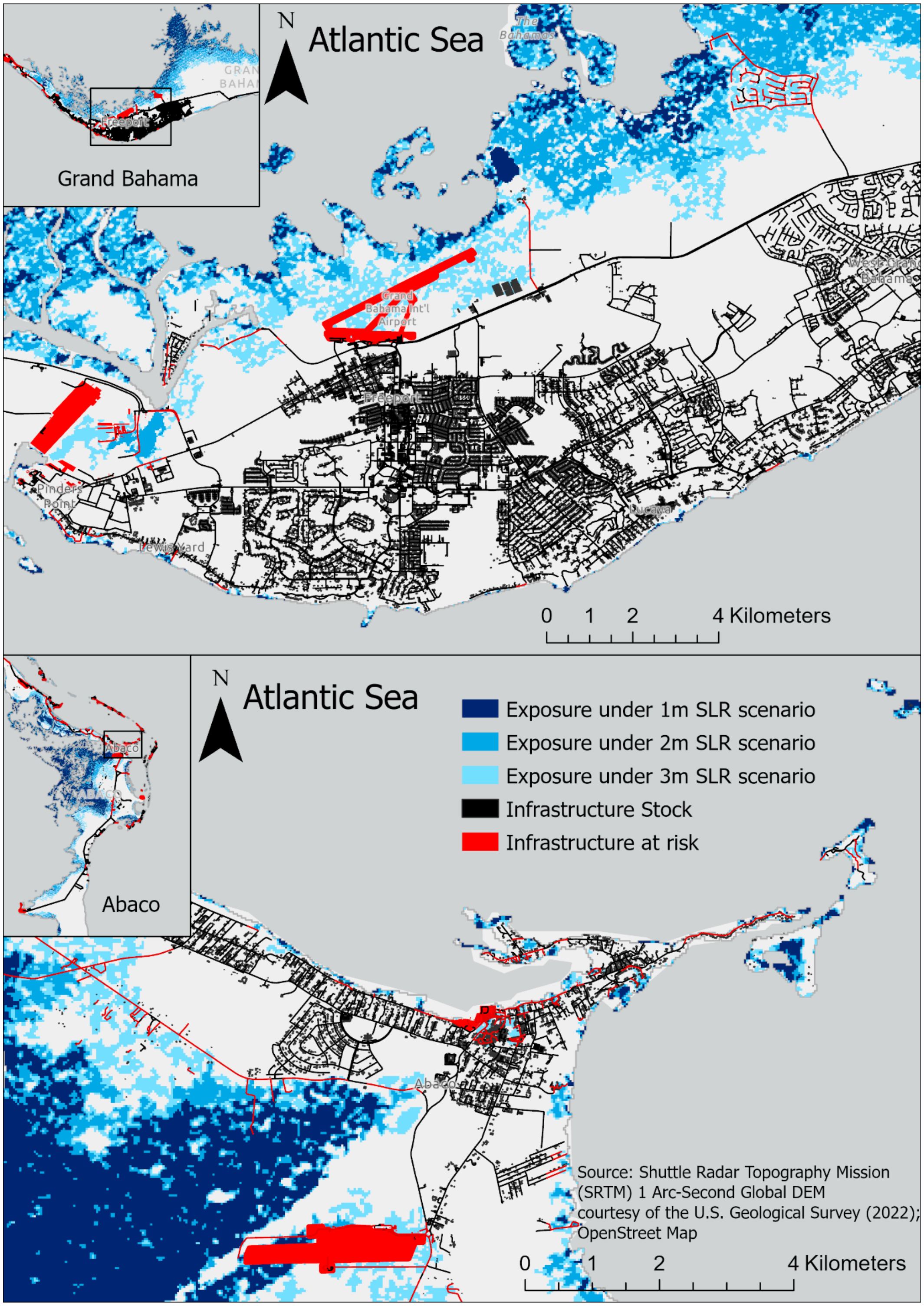
District name	Current building MS (mt)	RA$_{(g)}$ (m^2/m)	RL$_{(d)}$ (km)	GFA$_{(d)}$ (km^2)	5% of total future building MS (mt)	Current roads MS (mt)	Upgraded roads length (Km)	Future roads MS (mt)	Total future MS buildings + roads (mt)
Acklins	0.10	14.99	171	0.07	0.22	0.17	54.1	0.12	**0.34**
Berry 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**
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**

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.

5.5.3 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-meter 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-meter SLR scenario), while road stocks show the least transport exposure (see Figure 10 and Table 14).

Among buildings, residential and commercial MS show greater exposure in the three scenarios, with results varying from 0.2 mt 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.



Source: Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM courtesy of the U.S. Geological Survey (2022); OpenStreet Map

Figure 10 - Potential infrastructure at risk from SLR 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)

Most of the exposed building and road infrastructure 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 14 - The total existing MS exposed for each MS use-type under the different SLR scenarios in The Bahamas

SLR Scenario	**1 Meter**		**2 Meter**		**3 Meter**	
Material stock	**MS exposed (mt)**	**Use-type MS (%)**	**MS exposed (mt)**	**Use-type MS (%)**	**MS exposed (mt)**	**Use-type MS (%)**
Building use-type						
Residential	0.2	0.5	0.4	0.9	0.8	1.8
Commercial	0.2	0.4	0.2	0.6	0.4	1.0
Industrial	0.0	0.0	0.0	0.1	0.1	0.3
Government	0.0	0.0	0.0	0.0	0.0	0.0
Other	0.0	0.0	0.0	0.0	0.4	0.9
TOTAL	**0.4**	**0.9**	**0.7**	**1.6**	**1.8**	**4.1**
Road use-type						
Major subdivision roadway	0.1	0.6	0.2	1.4	0.5	2.9
Minor subdivision / local street	0.3	1.7	0.5	3.1	1.0	6.0
TOTAL	**0.4**	**2.3**	**0.7**	**4.5**	**1.4**	**8.8**
Airport structure						
Airport buildings	0.0	0.1	0.0	0.1	0.1	0.4
Airport runways	1.6	11.5	2.5	17.9	3.7	26.2
TOTAL	**1.6**	**11.6**	**2.5**	**18.0**	**3.7**	**26.6**
Seaport structure						
Seaport buildings	0.0	0.0	0.0	0.1	0.0	0.2
Seaport platforms	1.1	38.9	1.9	71.5	2.0	73.7
TOTAL	**1.1**	**38.9**	**1.9**	**71.6**	**2.0**	**73.9**
TOTAL MS EXPOSURE	**3.5**	**4.5**	**5.9**	**7.8**	**8.9**	**11.7**

Sources: based on estimates of global SLR by 2100 by Parris et al., (2012); 1 meter: intermediate-high projection; 2 meters: highest projection; 3 meters: extra simulation presenting a more critical situation where SLR continues to rise past the year 2100.

5.6 Discussion

5.6.1 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 climate change, air/water/soil pollution, noise, and ecosystems degradation, among others. In addition to being a contributor to climate change, transport MS is highly impacted by it (e.g., more floods due to rising sea levels). For residential and commercial buildings MS, the results of this Chapter reflect the importance that tourism has in the economy. As tourism has a heavy presence in the country (IBRD, 2021), there is an impending need to allocate resources to service this industry in the form of MS. However, the benefits produced by this sector (e.g., revenue, and job generation) oftentimes compete with the costs of tourism activities (e.g., a decline of coastal protection, and 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. Moreover, the Bahamian economy exhibits extractive resource patterns that are focused on only few key natural resources, including sand & 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). Moreover, with a low resource-base, the issue of import dependency over non-replaceable construction materials may be aggravated by price volatility and disruptions in the global supply chain, 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. Moreover, the long-term consequences and functioning of the system are essential considerations for resilience in small islands, especially in the context of climate change, natural hazards and development (Logan et al., 2022). Overall, each variable has its own dynamics, and simultaneously influences the others. 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 particularities of the case, based on the drivers and resource-use patterns, along with providing efficient and resilient infrastructure solutions in the face of climate change.

5.6.2 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. define socio-metabolic risks (SMRs) 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” (Singh et al., 2022, p. 2). In The Bahamas, the study revealed high MS density in specific urban centers, with uneven distribution across the national territory, oftentimes concentrated close to the coastline. Additionally, the availability, integrity, and circulation of critical resource flows are largely reliant on a combination of key MS. Furthermore, disturbances like climate change and SLR pose major threats to existing and future MS, contributing to the proliferation of SMRs. Table 15 offers an overview of potential current and future risks associated with the observed state of the country.

Table 15 - Potential current and future risks associated with the state of The Bahamas as seen in this analysis

Status of the country	Current Risks	Future Risks
(A) 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
(B) Infrastructure close to the coastline	Potential infrastructure damage/loss to extreme events, such as flooding or hurricanes.	Further infrastructure 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
(C) 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

Transport infrastructure in The Bahamas is one of the highest among the Caribbean SIDS (see Table 16), which can be partially attributed to the country’s location, geomorphology (an archipelagic country) and its vast territory. This heavy dependence on transport infrastructure—including seaports, airports, and roads—is required for everyday economic and social activities. Important economic sectors in the country rely on (coastal) transport systems (e.g., extractive industries, tourism, agriculture, fisheries) that are also highly vulnerable to climate variability and change factors like sea-level rise and extreme weather events.

Based on the results of this analysis, the largest affected stocks by sea-level rise are seaports and airports (see Table 14). Also, these stocks are of critical concern in The Bahamas when other extreme events strike. Hurricane Dorian impacted the Grand Bahama International Airport and the Leonard Thompson International Airport back in 2019, causing widespread damage and in the interruption of essential services that lasted for an extended period of time (Andone, 2019; Morgan, 2019). These airports are vital points for the islands of Grand Bahama and Abaco to connect with the rest of the world. With these destroyed, it would be difficult for communities in need to get aid or to leave, if they need to.

Other example of the importance of transport infrastructure and SMRs is related to fisheries and their infrastructure. These play an important role in economic development and food security in The Bahamas (FAO, 2017b). The negative effects of climate change continually affect the country’s limited material stocks linked to fisheries production, and transportation (e.g., like seaports, harbors, marinas and ferry terminals). The declining marine catch (FAO, 2021a) has been further impacted after Hurricane Dorian caused large-scale destruction of fisheries production and processing infrastructure, as well as damage to almost 80% of the already scarce fishing vessels (Kemp, 2019). Additional damage to these stocks could put at risk the overall food security and sustenance of the population, especially of those vulnerable groups.

Having a reliable and efficient transport network is especially critical for many sectors, since their proper functioning impacts on resource security, connectivity and the efficient mobilization of people and goods (ECLAC, 2011). 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, 2021a; NREL, 2015f; Symmes et al., 2019; Yu, 2017), any disruption in the operation of the transportation infrastructure (e.g. due to climate change and SLR) would have system’s-wide economic, social, and environmental 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.

Table 16 - Key seaports and airports data, by numbers and by per capita, for some SIDS around the world

Caribbean SIDS	Population 2020	Land area km^2	Inhabited islands	# of seaports	# of airports	Seaports per 10k inhabitants	Airports per 10k inhabitants
The Bahamas	393,244	14,000	17	8	67	0.20	1.70
Antigua & Barbuda	97,929	440	2	1	3	0.10	0.31
Barbados	287,375	430	1	1	2	0.04	0.07
Cuba	11,326,616	106,440	2	37	143	0.03	0.13
Dominica	71,986	750	1	3	2	0.42	0.28
Dominican Republic	10,847,910	48,320	1	14	42	0.01	0.04
Grenada	112,523	340	3	1	3	0.09	0.23
Haiti	11,402,528	27,560	1	11	21	0.01	0.02
Jamaica	2,961,167	10,830	1	15	27	0.05	0.09
St. Kitts and Nevis	53,199	260	2	2	2	0.38	0.38
St. Lucia	183,627	610	1	4	2	0.22	0.11
St. Vincent and the Grenadines	110,940	390	5	5	6	0.45	0.54
Trinidad & Tobago	1,399,488	5,130	2	11	3	0.08	0.02

Sources: OurAirports (2022); SeaRates (2022); The World Bank (2022i); World Port Source (2022); Worldometer (2022a).

Nonetheless, these risks should not be only understood only through the impacts of SLR on infrastructure stocks, but also on the compound and cascade effects that impact on other system's components.

- First, 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 (e.g., environmental pollution, and ecosystem health degradation) (see Table 15, number (A)). Along with emissions and ambience pollution, 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 overall health issues.
- Second, as The Bahamas is a low-lying country with relatively small islands, it is recognized that 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 salt water intrusion in surface and ground water, compromising the quality of water supply and food security for local people (see Table 15, number (B)). 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 island and Abaco island (see timelapse satellite imagery from Google Earth Pro® (2021)).
- 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 such as tourism (see Table

15, number (C)). Also, 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 socio-economic impacts of a potential 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 countries often spend large part of their public budget on transport infrastructure, either on regular maintenance or repairs from shocks (The World Bank, 2017). Moreover, the cascading effects arising from supply chain disruptions and critical infrastructure damage can spread through other components like other production or demand centers (e.g. power networks), thus further increasing the vulnerability of the system (Renn et al., 2020; Verschuur et al., 2022). SIDS could be considered mobility-constrained and highly dependent on transport for their trade and supply, as well as tourism industry. As transport infrastructure is key for the timely and efficient mobilization of resources, transport disruptions are one of the main obstacles to recovery when extreme events occur (United Nations, 2021a).

5.6.3 Open-source data and MSA

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

From the working OSM files, one can observed that few building footprints were missing from small zones, while the road network was virtually complete in the whole country. Following this Chapter’s 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, this 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 11). The utilization of this methodology and OSM data, thus, could be comparable to more established MS accounting methodologies.

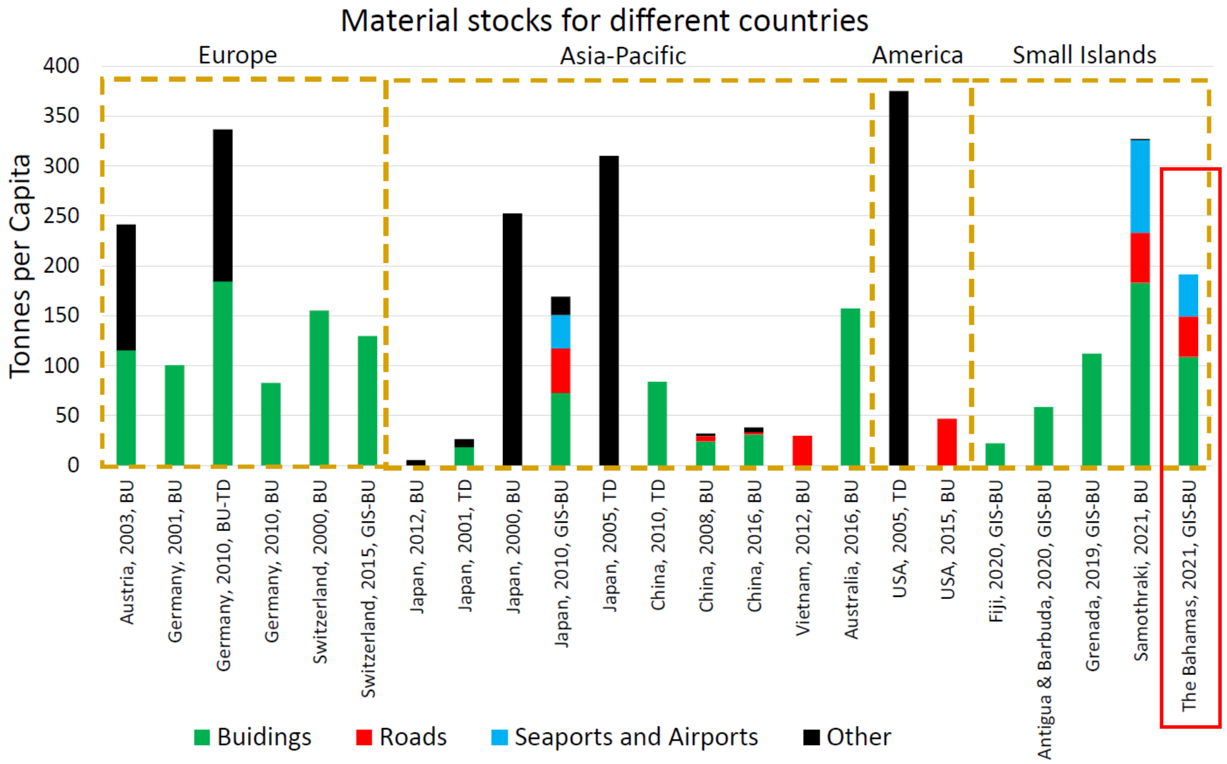


Figure 11 – Material Stock for different territories. Source: adapted from Lanau et al., (2019), with input from current study, Bradshaw et al., (2020); Merschroth et al., (2020); Nguyen et al., (2019); Noll et al., (2021); Soonsawad et al., (2022); Symmes et al., (2019); and Zhang et al., (2019). Abbreviations correspond to estimation approaches: BU: bottom-up, GIS-BU: GIS-based bottom-up, TD: top-down.

The potential advantages of OSM as main data source for MS assessments are profound. Similar to The Bahamas, spatially explicit data on buildings and infrastructure 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. Furthermore, OSM data is relatively rapidly updated by the crowdsourcing community, potentially enabling historical MS coverage analyses. The utilization of OSM data can also serve as a "predictive tool" to strategically map future development areas across the country for future land-use zoning and (risk) planning purposes. The results of the MS analysis managed to produce similar results for future development expansion (see Appendix C – Section 5, Figure C-9, and Figure C-10) as the ones proposed under the Andros Master Plan and Sustainable Nassau Plan (Government of The Bahamas, 2017, pp. 15, 16, 17; IDB, 2018, pp. 42, 43).

Nevertheless, care must be taken to ensure the quality and completeness of OSM data to reduce uncertainties. For example, in this study, historical OSM data were incomplete and thus prohibited a time-series assessment. Although some coverage is better than nothing, open-access crowdsourced data calls for extra scrutiny, highlighting the need for responsible use and clear reporting of results and uncertainties, and their potential implications. For The Bahamas, there are certainly uncertainties that originate from these data, but the lack of other data sources limits the assessment of these uncertainties beyond a simple qualitative assessment.

5.7 Summary of findings on the role of critical infrastructure on sustainability and resilience in small islands

This study comprehensively examines both Transport stocks and Building stocks for a small island nation as part of the MSA methodology based on freely available data. Specifically, the study estimated current and future infrastructure stocks by combining available GIS data from OpenStreetMap and data with stocks material intensities 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. Additionally, it underscores that these risks should not be only understood through the impacts of SLR on infrastructure stocks, but also on the amplification of risks due to the compounding effects of multiple hazards happening simultaneously or sequentially that affect other components of the system. We now turn to the main findings.

The existing infrastructure of the country urgently needs to be improved with a resilient and sustainable approach in mind. Critical infrastructure, particularly transport, is 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 all across the country. Future work in stock management must consider disaster risks, especially in a SIDS context. Attention should be given to identifying and mapping strategic areas for critical buildings, transport nodes, and networks to determine potential vulnerabilities and risks in the system. Moreover, future work should include an analysis of the most vulnerable social and ecological areas in the case of a possible coastal squeeze.

Although 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). Considering the looming threat of SLR, growing coastal urbanization, and limited space, attention should be given to hasten long-term development planning and adaptation strategies that contemplate the trade-offs of future infrastructure development in ecologically sensitive areas. Land and sea pressures over the natural ecosystems can cause a decline of these ecosystems, reducing their capacity to provide a wide range of essential services. Moreover, this decline would have a doubly negative impact through the loss of tourism resource-base and a decline in coastal protection, further increasing threats by SLR and storm surges.

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). The conservation of coastal ecosystems 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).

Finally, the precision of this analysis is dependent on the quality of the information available. This study gives a general overview of the potential that experimenting with open-source data may offer in advancing MS studies, and to what extent OpenStreetMap is helpful for the estimation of MS and as a "predictive tool" to strategically map future development areas across the country for future zoning and planning. As OSM data is freely available, this 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 (e.g., satellite imagery with OSM data and official statistics), giving a more robust representation of what is physically available on the ground. Further improvements regarding the infrastructure geodatabase mainly concern the accurate identification of infrastructure elements by use-type and the addition of unrecorded building footprints and road network segments, with more detailed material intensity data.

Chapter 6: Summary, contributions, and future research directions

6.1 Thesis summary

Our resource-use dynamics have contributed significantly to the improvement in global material standards of living through the provisioning of essential societal services. Nonetheless, these dynamics have also impacted on the already limited natural resource-base of the Earth system on which we depend. As such, the resource-use dynamics is posited as an important example of complex systems in need for better understanding, particularly in advancing towards sustainability and build system's resilience. Thus, dealing with sustainability would require a deeper understanding of the interactions and trade-offs between the resource-use and the influences that internal/external factors like climate change have over these.

The aim of this research is to explore the dynamics of socio-economic metabolism in the context of small islands as a potential approach to enhance resource security, reduce socio-metabolic risks, and build system's resilience. Both of the overarching research questions of finding the characteristics of the resource-use dynamics influencing over the SMRs in the island context, and the ways in which these resource-use dynamics could be influenced to enhance resource security and build system resilience were answered through Chapters 3, 4, and 5. Based on the points raised within this study, the analysis illustrates the importance of shifting our focus to identify the ways in which natural resources are interconnected, influenced, and managed in order to better illustrate how the resource-use dynamics can be adjusted to foster sustainable and resilient development.

On Chapter 3, the study demonstrates the immediate need to focus on the resource-bases of the territories as this is one of the characteristics influencing over socio-metabolic risks. In particular, the lack of an essential resource could already be considered as a risk. Moreover, from the analysis, one can see that there are the economic, social, and cultural aspects influencing over these. The manufacturing-base of the country, or even service sectors like tourism require a steady supply of resources to keep functioning. Coupled with consumer-habits and climate change, these further pressure over the limited resource-base and amplify socio-metabolic risk. Additionally, a focus on the intra-and interdependencies of critical resources is required in resource management and planning. This could serve as a potential plan of action to utilize resources more efficiently in a resource-stressed context like small islands. Managing, and mitigating SMRs can also be a very important strategy for policy interventions, which in turn would allow to adapt to, anticipate, resist, and recover from the climate change impacts that small islands are facing.

Along with regional cooperation, interventions must consider the wide range of realities within the region to properly identify potential barriers and openings for positive transformative change.

On Chapter 4, the study clearly demonstrates that specific resource patterns can contribute to the exposure to Socio-metabolic risks, for example, the dependency on external economies for basic resources, or not taking advantage of the resource-base of the territory. Also, internal factors such as current resource management strategies, particularly of outflows and circularity, influence on socio-metabolic risks Resource management is thus integral to properly managing systemic risks, especially in small islands. Inadequate resource management could adversely impact primary economic sectors (e.g., tourism), resource self-sufficiency, resilience, human and ecosystems health, and quality of life, among others. Identifying and reshaping metabolic profiles that exhibit systemic risks are a potential leverage strategy for small island economies to enhance resource security and build system resilience. As an example, one can devise strategies to sustainably manage the natural resource-base of the territory, through first understanding the scale, distribution, and composition of resource flows, and through designing strategies for the exploitation of the resource that, at the same time, account for the resource-bases, and current and future requirements of the population.

On Chapter 5, the study demonstrates that one of the main factors influencing on socio-metabolic risks is the built environment, which also plays a key role in sustainability. Within it, there are specific combinations of material stocks that are essential for the population. The use-type, their number, distribution, and other factors (like Climate change, SLR) may also contribute to current and future Socio-metabolic risks. Thus, the built environment urgently needs to be improved with a holistic, resilient and sustainable approach in mind. Moreover, with the looming threat of SLR, growing coastal urbanization, and limited space, the adaptation strategies, long-term planning and construction processes that contemplate the trade-offs of future development in ecologically sensitive areas are also one of the factors that could be influenced to enhance resource security and build system resilience. Attention should also be given to identifying and mapping strategic areas for critical buildings, transport nodes, and networks to determine potential vulnerabilities and risks in the system.

The study also highlights that:

- Sustainable resource management is integral to properly manage systemic risks, especially in resource-stressed context like small islands. A focus on the resource-baselines of the territory is suggested, first understanding the scale, distribution, and composition of resources, how these are connected and influence each other, and how these could entail Socio-metabolic Risk.

- Mitigating socio-metabolic risks by reconfiguring resource-use patterns can be a crucial adaptation strategy. Taking advantage of the resource-baseline, as well as the institutional and technical capacity of the territory, could position the economy in a more sustainable and competitive direction.
- Sustainable development will require a focus on the built environment. It has a critical role in the maintenance and creation of services, in driving material flows, in mitigating socio-metabolic risks and in advancing sustainability. The built environment requires efficient planning, construction processes and designs, demanding for an efficient use of resources, with low and controlled emissions and waste, along with providing resilient infrastructure solutions in the face of climate change.
- There is a wide reality from territory to territory, each with varying combinations of social, economic, and environmental characteristics. Along with regional cooperation, strategies should encompass a holistic long-term sustainability vision that is flexible, adaptive and that is supported by an effective regulatory and institutional framework that allows for context-specific implementations. Doing so will aid to properly identify potential barriers and openings for positive transformative change.

6.2 Thesis contributions

This research makes several important contributions.

- **Contextually -** This study provides a much-needed analysis of the resource-use dynamics in small islands, particularly of the Caribbean, from a Socio-metabolic Research perspective. As this type of analysis has not been widely undertaken, this is an important aspect that strengthens the literature.
- **Conceptually -** This study analyzed resource-use dynamics through the emerging concept of socio-metabolic risks. Although several other studies have provided important insights into resource-use dynamics, these have not explicitly mapped and identified associated SMRs and cascading effects within and across sectors, especially in an island context. This study takes a novel approach to resource-use dynamics through a system’s wide approach.

- **Methodologically** – This study advances knowledge on overall Socio-metabolic Research and Industrial Ecology through the application of tools and concepts such as the WEF-Nexus, by proposing a new approach to analyze these resources through the dimensions of availability, access, consumption, and self-sufficiency; through the application of both economy-wide material flow analysis and circularity principles to map the biophysical basis of island economies; and the application of both GIS and freely available OpenStreetMap data to assess current and future material stock vulnerability and resilience.
- **Replicability -** As most of the data sources utilized in this study are freely available (UN Comtrade Database, FAO Food Balance Sheets Database, FAO AQUASTAT Database, Energy Information Administration Database, OpenStreetMap, etc.), the approach taken in this study can be easily replicated in many other territories with relatively low time and resource investments, especially for other small islands and developing countries.

Overall, this study urges to plan for sustainability as a whole system in a context-specific situation, by understanding and characterizing current resources baselines, the patterns of resource-use within the socio-ecologic system, and the role that critical stocks and flows play in the evolution of society-nature interactions. This makes possible to ensure detailed consideration of the features of each case while recognizing common factors, fostering greater learning capacity, and defining desirable positive functionality where one can direct tipping points to prompt transformations that can drive climate action, resource security and build system's resilience. Thus, an explorative examination highlights the favorable elements, as well as the barriers, to boost sustainability benefits in specific contexts.

This study emphasizes measures for strengthening resources and economic security and resilience and strives to create a more functional and productive public dialogue for resources security and sustainability. The outcomes of this study contribute to a more general vision of material flows and stocks and sustainability on small islands, as well as to provide an opportunity to better understand the dynamics between infrastructure stocks, resources requirements and climate change. Concluding arguments from this study highlight merits and deficiencies of sustainability management for each standalone empirical article and as a collective learning project. In this sense, the analysis of the data collected reflects the recent struggles and successes of local and regional system planning to address the impacts of socio-ecological effects that stem from conventional systems' design. Hence, findings from the application of the approach to each standalone empirical article aim at providing valuable lessons for further study and/or action.

6.3 Policy relevance

Governance and policy are key to understanding, analyzing and shaping transformations towards sustainability (Patterson et al., 2017). However, effective information, governance and institutional agreements are needed across the full range of sectors, actors, institutions, and activities involved in the socio-metabolic systems, including those managing essential natural resources as well as infrastructure and global trade. Despite significant improvements in the provisioning of essential resources and services to a growing population, our current resource-use dynamics have created several challenges that may potentially generate SMRs and cascading effects and that in turn could lead to metabolic collapse if not properly managed, especially in resource-stressed systems like small islands. Actions in support of a sustainable, resource-secure, and resilient system are urgently required to be implemented in a comprehensive and holistic way, with continuous monitoring and follow-up. The relevance of evolving from traditional approaches in support of specific problematic resources or sectors towards a more holistic approach to enhance resource security and resilience is thus critical for sustainability and SMRs mitigation (Schweizer, 2021).

In addition, addressing climate change as one of the stressors of socio-metabolic risks represents an opportunity to build resilience in a meaningful and comprehensive way through the adoption of interconnected governance processes. Strengthening governance related to risks and coordination across the full range of sectors, actors, institutions, and activities involved in the socio-metabolic systems at appropriate levels strengthens the system for prevention, mitigation, preparedness, response, recovery and rehabilitation in case of SMRs and disasters (United Nations, 2015). Governance of natural resources should also aim at enabling the sustainable ordering and planning of the territory, coordinating to enable a social, economic, administrative, and political environment, at building a sustainable and circular value chain, and at develop and strengthen data platforms that deliver information for the design of strategies and the creation of new competitive and sustainable markets.

The analysis of resource-use dynamics from a socio-metabolic research perspective can be used for early recognition and priority setting for socio-metabolic risks and the implementation of solutions, by means of highlighting the natural resource-bases, flows, stocks, and changes in natural and anthropogenic processes. In this study, one can observe special vulnerabilities that influence over SMRs, like deficient waste management system, a heavy dependence on imports for basic needs, low levels of energy self-sufficiency, and more. Decision-makers can then devise strategies in line with these dynamics and aim to achieve long-term resilience and sustainability (e.g., through banning of single use plastics, investments in renewable energy generation and domestic food production, etc.). Also, our study can be useful to analyze and improve the effectiveness of established measures, by evaluating the progress through time of these dynamics through scenario simulations and trend projections (e.g., as in the case of the renewable energy targets across the Caribbean region). Moreover, this study can be a powerful communication tool. Through the use of spidergrams (in Chapter 3), to the use of Sankey diagrams (in Chapter 4), and maps on sea-level rise scenarios (in Chapter 5), the results can be easily conveyed to the public and decision-makers. Engaging with the stakeholders could provide them with extra information about the risk faced, about what actions to take to minimize risk and potentials to induce positive tipping points. Doing so can facilitate progress toward sustainability and empower communities, especially those living in vulnerable conditions, to adapt and transform into a resource-secure and resilient society. Through capacity building and information sharing, the whole society and vulnerable groups can benefit from effective governance and policy measures, possibly leading to situation of reduced SMRs and more political and resource stability, and the improving of the enabling environment in which resource security, SMRs mitigation, and climate change adaptation takes place (Gheuens et al., 2019).

6.4 Key findings

6.4.1 The interconnected nature of resources

Small Islands states can be found across the world, in the Pacific, in the Africa, Indian Ocean, Mediterranean and South China Sea, and in the Caribbean. All share similar characteristics of limited natural resource base, growing trends in resource demand, rapid urbanization and other complex pressures. From our empirical findings and throughout Chapters 3, 4, and 5, one can see that natural resources are closely connected through a complex network of interactions (e.g., like economic markets, global trade, urban expansion, or ecosystems, among others) that influence on the functioning of the system.

From Chapter 3, one can see that this is especially the case in Caribbean small islands as the trends in the region exhibit increasing water shortages, with projections to experience even more water scarcity in the future, potentially cascading in social unrest, and political and socio-economic instability. Also, the still growing regional dependency on imported fossil fuels and low renewable energy generation can be seen as early indicators of concern for country-wide energy security. With energy provisioning systems that exhibit some deficiencies, the region is at risk of energy shortages due to the disruption in supply that can quickly impact on other essential sectors, especially in case of disasters. Additionally, as the region has steadily become consumers of non-traditional and nutritionally inferior foodstuffs, the overall food security and nutrition is at risk, which in the long run could impair human development and even trap the population in an intergenerational cycle of malnutrition, poverty and health issues, among others.

Meanwhile, from Chapter 4 and Chapter 5, one can see that specific resource-use dynamics (e.g., fossil fuel dependency, imports of resources for basic needs, the expansion of the built environment, high waste generation, etc.) could adversely impact primary economic sectors (e.g., tourism), resource self-sufficiency, resilience, human and ecosystems health, and quality of life, among others. At the same time, the Caribbean small islands and The Bahamas show higher impacts on livelihoods and damage due to climate-related disasters according to the International Disaster Database (EM-DAT & CRED, 2022). Other than the most evident human and material losses, these disasters also result in the immediate interruption of critical services that directly impact on the overall livelihoods, resource security and resilience of the island system.

Broadly, one can see that the natural capital in the planet is also interconnected through multiple ecological interactions, which provide many ecosystem services that society benefits from. These dynamics have been present since ancient times and have allowed our society’s evolution and coexistence. Nonetheless, not all the interactions are mutually beneficial and, in general, there is a great deal of elements directly involved in each interaction. As of today, almost every aspect of nature has been impacted by human activities. At a broader scale, the loss of an essential link in the network (e.g., loss of the resource-base) also means the loss of its interactions, which in turn alters the resource-use dynamics and completely changes the structure and functioning of the system.

This way of seeing things could allow us to approach the problematic in a more holistic way through the study of the collective and organized behavior of its parts. Within a system, one can find a small group of essential elements that interact with each other in a greater extent, and other groups of elements interacting in a lesser extent, however all contribute to the functionality of the system. The absence of one element could interrupt a critical process necessary for survival, bringing cascading effects that could potentially lead to system’s collapse. As a result, one could induce positive tipping points by means of reconfiguring the structure and arrangement of the metabolic system to bring functionality, stability, and resilience in the long run. In particular, the interconnected nature of resource-use dynamics in society is posited as an important example of complex systems in need for better understanding, particularly in advancing towards sustainability and build system’s resilience.

6.4.2 The built environment

The built environment generally refers to the man-made surroundings that provide the setting for human activity, ranging from the large-scale built surroundings to the personal-use space. In the case studies analyzed through Chapters 3, 4, and 5, one can see that the built environment, inclusive of buildings, infrastructures, machinery, etc., has a critical role in driving material flows/throughput of a society, in the transformation of resources into useful services, as well as in mitigating SMRs and in advancing sustainability.

From Chapter 3, one can see that the Caribbean region is falling behind in upgrading essential infrastructure to support its people’s livelihoods and those of generations to come. Based on the trends of declining water availability, efforts are still needed in preparation for future water scarcity as only few Caribbean SIDS have begun to implement water desalination technologies as alternative source of water supply. Moreover, the region’s (deficient) energy provisioning systems, which are largely dependent on fossil fuels, are also physically exposed to frequent disasters. Future affectations on this type of infrastructure can cause a disruption in the energy supply, which can present an existential threat that may lead to dangerous and unpredictable risks on water, energy and food security, as well as on other essential sectors across the Caribbean SIDS. Additionally, food security is heavily dependent on sustainable, resilient, inclusive, and efficient systems of production and consumption, especially in the Caribbean region. For foodstuff-related sectors (inclusive of agricultural, livestock and fisheries), there may be tipping points that rapidly accelerate due to cumulative pressures (e.g., climate exposure, deficient fishing fleet and facilities, outdated irrigation technologies, deficient energy provisioning systems, and vulnerable transportation systems) that contribute to the further degradation of vital infrastructure and that threaten island habitability and resource security.

Meanwhile, from the case study analyzed in Chapter 4 and 5, one can see that having a resilient built environment is a prerequisite for sustainable development and resource security, especially in the face of new and emerging challenges. The Bahamas, being a net-importing country, utilizes seaports, airports, and roads for the timely and efficient mobilization of people and resources from within the country and from/to external economies. Also, the Bahamian built environment is an important provider of services critical to achieve sustainability. At the same time, the country’s built environment is located in areas along the coastline are highly susceptible to the most common types of hazard (e.g., more floods due to rising sea levels). Consequently, environmental hazards have catastrophic impacts on exposed infrastructure, contributing to human and material losses and other cascade effects.

In general terms, the contribution of the built environment towards global sustainability is important. On one hand, buildings contribute significantly to the global environmental load caused by human activities by being the largest energy-consuming sector in the world (close to 40%) and having emissions of around 30% of global annual GHG (Unalan et al., 2016). In addition, the built environment is responsible of more than 30% of the world's resources depletion, of more than 10% of water consumption, and of around 40% of waste going to landfills (Langston et al., 2008). On the other hand, construction is a major industry throughout the world accounting for a sizeable proportion of the GDP for most of developed and underdeveloped countries (Crosthwaite, 2000). As such, the future development of society and the built environment will require a focus on the sustainable expansion of the built stocks (infrastructure) and the maintenance and creation of services, with consideration on alternatives to adapt, reduce and mitigate the impacts over air, water, soil, mobility, the environment and society. It requires efficient planning, construction processes and designs, demanding for an efficient use of natural resources, with low and controlled emissions and waste. The built environment should be seen as a "stepping stone" towards sustainability, providing essential services to society, while integrating approaches that aid to mitigate and adapt to the negative effects of climate change and SMRs.

6.5 Future research directions

6.5.1 Critical resources

In Chapter 3, this thesis analyzed three resource-bases closely interrelated and essential for the proper functioning of the island system. It attempts to encompass most of the characteristics of these dynamics of resource-use in an effort to reveal certain combinations that could entail SMRs through the analysis of 4 proposed dimensions: availability, access, consumption and self-sufficiency, and in two points in time. External factors such as climate impacts are also considered in this analysis, as these could exacerbate or alleviate SMRs. However, the island system is not only dependent on water, energy, and food for its proper functioning but on many other critical materials, all with their own relative degree of importance within the system. Particularly in the island system, their already limited resource-base could be further threatened depending on how these resources are managed, bringing an array of potential SMRs and cascading effects. Future studies should also include the analysis of other type of resources of the resource-base and the inclusion of economic shocks, and other stressors in the analysis of SMRs. Besides the identification of the resource-base availability, studies on the identification of a balanced resource extraction that maximizes natural and human well-being and that do not compromise the continuity and ability to utilize the resource is needed.

Additionally, future research should also look beyond the analyzed dimensions of availability, access, consumption, and self-sufficiency, and include other dimensions like the social and political (un)acceptability of socio-metabolic risks and mitigation strategies. For SMR mitigation strategies to be better evaluated, these need to analyze the costs and benefits, including in terms of risk acceptability while considering the socio-economic context in which these will be applied, together with the needs, issues, and concerns of the stakeholders involved. By aligning these solutions with the values, needs, preferences and expectations of the society and searching for socially acceptable and desirable futures can help bridge the gap between research and implementation of strategies to minimize risks. Socio-metabolic research should be context-specific in order to deepen our knowledge and provide an adequate approach to the problematic. This will allow us to establish corrective actions to the system, which will help to develop alternative resource management models that will minimize SMRs and build system resilience.

6.5.2 Material flows, stocks and circularity

In Chapter 4, this thesis performed an economy-wide mass-balance account of socio-economic flows for a single Caribbean SIDS that draws from circular economy principles. It provides consistent estimations for current metabolic levels and establishes the metabolic profile of the case-study in a single point in time. Moreover, the Chapter 4 explores the interdependence between socio-economic sectors driving the demand for resources and identifies SMRs, cascading effects and potentials for building circularity and resilience in the island context. The identified resource-use dynamics have contributed significantly to the improvement in material standards of living through the provisioning of essential societal services. Nonetheless, these have also contributed to a self- perpetuating linearity that only increases demand for limited raw materials and continues to generate high waste that remains unrecovered. This linearity of material flows should include a more circular vision.

Circular economy aims to create a system of utilization of resources that becomes so efficient in the use of materials that it minimizes resource extraction and the overall degradation of nature. The challenge consists of designing and implementing a holistic long-term strategy that enables a socio-metabolic model that goes beyond refusing, reducing, reusing, repurposing, and recycling, and in which organizations of all types and levels contribute to the management of waste streams and that will contribute to pinpoint system metabolism levels, as well as future options for circularity and materials loop-closing. On this way, the value of products, materials, and overall resources that we benefit from will be utilized within the socio-economic system for the longest time possible, and waste generation will be reduced to a minimum volume. As such, the adoption of circular economy as a core element in sustainability can contribute to helping small islands think systematically about their socio-economic metabolism, ameliorating the pressures over natural resources and transitioning to a more resilient and resource-secure island system.

To better design a circular model that maximizes the utilization of natural resources and to give a more complete interpretation of the results at a regional level, future work on the analysis of socio-economic flows should include a more in-depth analysis of the interconnections of resources and of the flows of materials throughout the economy. There is a need for a more disaggregated analysis on the size and composition of the materials flows, as well as better metabolism indicators that characterize and improve the knowledge of the inputs, the in-use and reutilization of resources, and processes influencing over waste generation and recycling streams, as well as the interactions between sectors influencing trade-offs and synergies in the island system. As the nature of the system is dynamic, future work should also include the evolution in time of the socio-economic flows, highlighting trade-offs and synergic effects that alleviate or exacerbate SMRs and cascading effects in the individual island system and at a regional level.

In Chapter 5, this thesis analyzes masses and distribution of material stocks and their vulnerability to the impacts of climate change for a single Caribbean SIDS. It considers the spatial distribution of infrastructure, their typologies, the masses of materials in them, its overall structure composition, and maps critical infrastructure threatened by sea level rise using statistical data. It offers a quantitative and qualitative view of how the material stocks are spatially distributed and impacted by sea level rise, and how these stocks play a major role as drivers of resources flows and in the provisioning of services. Overall, the results of this Chapter 5 show different impacts over the building stock that exacerbate the system's vulnerability and increases potential SMRs. Long-term projections like the growth in travel and tourism suggest an increase in material stock and flows (demolitions and waste), which in turn calls for strategies to manage materials, land, and future outflows. The growth in population and material stock, together with economic activities like tourism seem to pressure the island system into finding ways to cope with the demand of resources. To give a more complete interpretation of the results in a regional level, next steps should include a broader comparison of several material stocks intensities for all Caribbean SIDS, a consideration of indicators of sustainability to assess the effect of materials flows from infrastructure stock on the environment, a sensitivity analysis for material flows during all phases of the infrastructure's life, and more complete studies of potential SMRs in combination with simulations of sea level rise and other climate-related impacts.

6.5.3 The role of services

Douglas highlights the fragile environments and ecosystems of island nations, alongside the challenges of urbanized zones, mostly tourism driven, creating imbalances with the rural and coastal areas (Douglas, 2006). Most of the islands in the world provide tourism-related services that represent a large share of their GDP. At the same time, these services demand improved amenities and prompt growth in major centers. This physical and economic growth often result in the development of the built environment, and this therefore calls for a wide range of public services and resources in such locations. However, the benefits produced by this sector (e.g., revenue, and job generation) oftentimes compete with the costs of tourism activities (e.g., a decline of coastal protection, and environmental degradation). The sustainability in the tourism sector should include the reduction of the SMRs arising from the human-nature interactions, as well as within society, and between tourists, residents, and the organizations managing tourism-related services. Sufficient resource allocation to ensure the stability and quality of the service among the population is required, thus care should be taken as plans have to accommodate for the current and future resource-bases of the territory.

Moreover, it is important to understand how these island communities and their governments perceive their own actions in response to these challenges, and the degree of importance they place on key social economic and ecological factors. However, the sustainable management of natural resources for tourism does not immediately translate in sustainability for the whole system as it is only a small component of the whole. As such, the holistic view of the problem would require the inclusion of an analysis of other economic sectors. We need a better understanding of usage of resources and consider the links between the main economic activities (e.g., tourism), material and energy flows, and the effects of usage rates and intensities on present and future generations.

6.5.4 Nature-based solutions

One of the most promising development strategies that could sustainably enhance resource security, build system’s resilience, and prevent and adapt to climate change are Nature-based Solutions (NbS). NbS are actions and policies dedicated to protect, manage, and restore the natural and modified ecosystems in a sustainable way. NbS approach these societal challenges effectively and adaptatively in a way that fosters resilience, simultaneously benefiting both nature and the population. NbS are underpinned by benefits that stem from healthy ecosystems. They target major challenges like climate change, disaster risk reduction, resource security, biodiversity loss and human wellbeing, and are critical from a sustainable development perspective (IUCN, 2022; WWF, 2022b), and have served as a guiding principle for sustainable development across the world (Bjerre et al., 2021; Cohen-Shacham et al., 2016; Dudley & UNDP, 2010; IUCN, 2012; IUCN French Committee, 2019; Millennium Ecosystem Assessment, 2005; United Nations, 2015, 2022b). If effectively designed and implemented, they can serve as a foundation for long-term economically viable and sustainable development, often less costly than technological investments, or the construction or maintenance of infrastructure-related projects.

More specific projects, guidelines and initiatives have focused on an umbrella of application of NbS for the management of resources and sustainable solutions in the face of climate change and risks, such as in freshwater management (Abell et al., 2017; Gardner et al., 2015; Sambalino & Steenbergen, 2012; UN Environment-DHI et al., 2018; UN-Water, 2018; WWAP/UN-Water, 2018), energy conservation and efficiency (Crowther et al., 2021; Fund, 2019; Principality of Monaco, 2019; Sabo & Booth, 2019; The World Bank, 2013), the agrifood system, food security, land use conservation (Amazon Sacred Headwaters Initiative, 2022; JRT Secretariat, 2022; The Food and Land Use Coalition, 2022; UNCCD, 2022; WBCSD, 2022), resources and infrastructure risk management linking to other resources (ADB, 2016; Buyck et al., 2017; CNT, 2011; FABLE Consortium, 2019; Global Mangrove Alliance, 2019; E. Gray et al., 2013; Krchnak et al., 2011; ORRAA, 2022; Ozment et al., 2015; UNEP, 2014c; WWF, 2017), and climate change mitigation and adaptation (Central African Forest Initiative, 2022; Government of Costa Rica, 2019; Nature-based Solutions Coalition, 2019; OECD, 2020a; UN-REDD, 2020; K. Zhang et al., 2022), among many more.

Similarly, we can find NbS developed and implemented in the context of small islands (Barnett et al., 2022; Lecerf et al., 2021; World Team Project, 2019), including through the establishment of sustainable electricity generation and forest management in Papua New Guinea (Government of Papua New Guinea, 2018, 2019), the Blue Carbon Initiative and ecosystem-based-adaptation strategies for Indonesia, the Philippines and Micronesia (Conservation International, 2019; Rare, 2019), ocean conservation and sustainable communities in Fiji (Government of Fiji, 2019, 2020), urban green spaces in Mediterranean islands (Grace et al., 2021), ocean conservation, resilience and climate-change adaptation in pacific SIDS (Barnett et al., 2022; Kiddle et al., 2021; Pedersen Zari et al., 2019; Prasad et al., 2022), coastal management in Singapore (CLC, 2022), infrastructure development and resources management in Caribbean SIDS

(Ozment et al., 2021), disaster resilience in Jamaica (S. Lee et al., 2022), coastal vulnerabilities minimization in the British Virgin Islands (Soanes et al., 2021), in ocean ecosystems management in Grenada (Government of Grenada, 2019), and in many others.

As seen by the examples above, international projects, guidelines and initiatives encourage an expansion of NbS worldwide, as well as governance approaches that are more participatory and collaborative. Sustainable management of environment and natural resources through NbS is thus essential for the long-term and sustainable growth of key economic sectors relevant across SIDS. In addition to being important generators of GDP and beneficial to the human well-being, natural resources also provide a range of ecosystem services that play a critical role in the countries' efforts to reduce SMRs and adapt to climate change. Nonetheless, care should be exerted as natural resources challenges are context-specific and subjected to rapid social-ecological changes. As such, empirical research on NbS that highlights the trade-offs and synergies between different resource-use patterns and socio-metabolic systems are critical when exploring potential plans for sustainable and resilient development.

6.5.5 Socio-metabolic risks

The study analyzed resource-use dynamics in small islands territories through the emerging concept of socio-metabolic risks. The analysis showcased a variety of special vulnerabilities related to anthropogenic and natural drivers that influence on the identified socio-metabolic risks. These risks include a deficient waste management system, declining levels of the natural resource-bases, a system heavy dependence on imports for basic resource needs, with low levels of energy self-sufficiency, a vulnerable infrastructure concentrated in specific urban centers at close proximity to the coastline, and more. Together with other complex social, economic, structural and climate pressures that further exacerbate their vulnerability, the study also highlights that the overall resource security and sustainability of small island territories are under threat. The approach taken in this study demonstrates that effectively, and clearly identifying SMRs could serve as leverage points to articulate adaptation strategies and for building resource security and system's resilience.

The overall study adopts a combined quantitative and qualitative approach to identify these risks in which the qualitative part is performed through an assessment of the quantitative part of the analysis. As such, the study is limited due to not having an established definitive index, scale, or threshold specifically for evaluating SMRs. A first attempt to quantify SMRs was made throughout this study, through quantifying resource-use dynamics of water-energy-food from the dimensions of availability, access, consumption, and self-sufficiency (Chapter 3), through quantifying the metabolic profile in The Bahamas (Chapter 4), and through quantifying material stocks and its affectation from sea-level rise in The Bahamas(Chapter 5). However, the overall study could benefit from an improved quantitative analysis that could be comparable with established global risk reports. As such, future work should aim to establish an index, scale, or threshold specifically for evaluating SMRs that it's coherent and helps stakeholders to understand the relationship between the metrics as well as the metrics themselves. The development of a measurement framework can aid in understanding and communicating the most effective way to reach the SMRs minimization strategies' goals and objectives.

6.6 Research limitations

6.6.1 Datasets

In this thesis, the direct collection of on-site primary data was not possible and the analysis had to rely on remote data collection. Overall, the limited data availability presented numerous setbacks and constrained the scope, precision, and depth in this research. Although having better datasets would be useful, the general messages that this study aims to communicate can still be seen as valid.

In Chapter 3, due to limitations on the databases for water, energy, and food across all four dimensions of availability, access, consumption and self-sufficiency, the thesis included the analysis of only 14 Caribbean small islands, leaving out of the analysis to small islands like the British Virgin Islands, Puerto Rico, Sint Maarten, and others. Additionally, from the 14 Caribbean small islands analyzed in this Chapter, statistics for the resource Food for Aruba were unavailable, and only general reports on the agrifood system in Aruba were available. This study recognizes that data was compiled through different data sources as national statistics were lacking. This is an important aspect in managing uncertainty and inconsistencies in definitions, data collection methodologies, and completeness. A more comprehensive and holistic analysis requires a robust and reliable database. There can be no meaningful regional database without the existence of national databases on which to draw. Having better data, e.g., national statistics generated from the individual country's statistics division, would provide a more accurate representation of each country's profile, which would translate into more reliable and granular results in the analysis.

In Chapter 4, it was attempted to define the metabolic profile of the case study through an analysis of resources flowing through the island system. Trade data was one of the basis for this analysis. Most of the data sources were compiled and processed from international sources believed to be reliable as national statistics were not available or very scarce, however, it was advised that these should be considered with a degree of caution due to global inconsistencies in definitions, data collection methodologies, and completeness. A refined representation of the metabolic profile of the case study was constrained by the levels of disaggregation presented on these databases. This is particularly reflected in this Chapter's case study through the Rotterdam effect. Moreover, data deficiencies in terms of domestic extraction and waste generation and recycling further limited the precision of the analysis. With access to more complete national statistics, the analysis would have been benefited for the economy-wide MFA. It would have also provided more detailed results on the potentials for circularity in the system, providing a more comprehensive representation of the metabolic profile of the case study, which in turn would have allowed for a better understanding and interpretation of associated SMRs and potentials for SMRs mitigation. Nonetheless, our analysis which draws from international data sources gives a robust panorama of the state of the system.

In Chapter 5, the generation of estimates on the material stocks of buildings and transport for the case study was constrained by the datasets utilized. In this study, spatial databases containing information on the building footprints were analyzed, however, the quality of the spatial database was also limited, with some spatial data missing from small zones. This Chapter's study thus suffered a small setback in the precision of the analysis as one would be unable to generate consistent material stocks estimates for places that do not have any existing building or road segments recorded in the spatial databases yet. Moreover, studies on material intensities, especially for buildings were non-existent for that case study. Assumptions had to be made based on similar typologies and intensities for evaluation purposes. Having access to more complete studies, reports, and geospatial databases on material stocks and material typologies and intensities would aid in minimizing inconsistencies in estimates of material stocks and sea-level rise simulations, as well as in the interpretation of SMRs across the case study.

Despite these data deficiencies and challenges, the analysis and subsequent results from Chapters 3, 4, and 5 are in line with other studies and reports, which provide a degree of certainty and validate the findings. Chapter 3 is comparable to other independent studies on water (Winters et al., 2022), energy (OECD et al., 2021; Surroop et al., 2018), and food (Caribbean Public Health Agency, 2017; Rahman et al., 2022). Additionally, the characterization of SMRs is consistent with different reports on water (e.g., ECLAC, 2022; Holding et al., 2016; UN, 2021; UNESCO-IHP & UNEP, 2017), energy (e.g., Degnarain, 2020; ECLAC, 2020; WHO, 2022b), and food (e.g., (CARICOM, 2016; CARPHA, 2021; FAO et al., 2021) (CARICOM, 2016; CARPHA, 2021). Similarly for Chapter 4, the results of the ew-MFA fall within the range of other studies (see Table 9), and also align with independent reports related to SMRs (e.g., IDB, 2016; Kaza et al., 2018; Mohee et al., 2015; UNISDR, 2015). In addition, the analysis of Chapter 5 can be comparable to more established MS accounting studies (see Figure 11), and reports related to SMRs (e.g., Bello, Hendrickson, et al., 2020; ECLAC, 2020; The World Bank, 2017; Verschuur et al., 2022).

Overall, SIDS experience considerable adversities that require special cross-sectoral assistance to achieve sustainable development and both individual and collective internationally agreed goals. The capacity of an island system to be resource-secure and resilient may be determined by measuring its vulnerability to SMRs and external shocks, which may be achieved through the use of indicators (ECLAC, 2011). Closer monitoring on the biophysical basis of island systems is thus essential for a proper management of their natural resources. However, addressing vulnerability and building resilience in SIDS would require addressing data gaps. For SIDS, characteristics such as limited national physical and human resources, small domestic markets and underdeveloped institutional infrastructures, vulnerability to natural disasters and to the negative effects of climate change have negatively influenced over economic and social development. A number of the aforementioned characteristics have resulted in poor national information systems and to the non-disclosure of information (Busby, 2003; UNEP, 2014b). Priority should be given to strengthening capacity-building of reliable, robust and accurate data to identify, collect, test, and validate appropriate indicators to address nationally-identified sustainable development priorities (Zitoun et al., 2020). This would require standardizing the concepts, definitions and measuring instruments that determined economic and social status and progress (ECLAC, 2011; UNEP, 2014b).

6.6.2 Methodology

Material flows and stocks accounting considers the inputs and outputs of materials and energy and its flows to estimate the material and energy intensity and predicting future flows in a socio-economic system. However, the establishment of links between inflows and outflows and different consumption and production activities is limited and this impact on the ability to properly identify the metabolic profile of the system. Detailed description of the ways in which resources enter the socio-economic system for further processing or consumption, the ways in resources accumulate as stocks, and the ways resources exit and re-enter the economic processing system are also indirectly visible, which further limits the comprehension of the dynamics of resource-use in the system. Although the Chapter 3, 4, and 5 of this thesis have provided important insights into material flows and stocks and drivers of resource-use, they have not fully incorporated an analysis of the internal and external processes that influence on the overall dynamics. One general improvement over the material flows and stocks accounting approach could be the Material Stock-

Flow-Service Nexus approach. The methodological advantage of the Material Stock-Flow-Service Nexus approach addresses the need for material stock accounts, differentiation between different types of materials and, at the same time, addresses their different functions that these materials provide within the socio-economic framework of the research area. The Material Stock-Flow-Service Nexus could give us further insights on the interrelations between material and energy flows, socio-economic material stocks, and the services provided by these combinations of stocks/flows (Haberl et al., 2017).

In addition, the material stocks and flows analysis could benefit from the inclusion of detailed Geographical Information Systems (GIS) methodologies and tools. Material stocks and flows accounting, coupled with GIS methodologies and tools could aid in identifying and mapping the natural resource-bases of island systems, which in turn could aid in developing strategies to the sustainable use of these, as well as mitigating potential SMRs (Azapagic et al., 2007; Ghani et al., 2017; Lella et al., 2018; Wallsten et al., 2015). Moreover, the GIS methodology has three major benefits that could be combined to a traditional material stocks and flows accounting to enhance its analysis: firstly, the ability to modify the scope of spatial units for analysis make spatial allocation readily applicable in the multilevel spatial planning regime and environmental governance (town, city, municipality, estate, province, national, etc.); secondly, spatial allocation offers a platform for joining bottom–up and top–down approaches; and finally, the indirect and temporal nature of the spatial attributes makes spatial allocation applicable to a wide range of spatial units, offering a particular advantage in establishing a more complete static analysis and into predicting future trends (Roy et al., 2010).

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Appendix A - The resource (inter)dependency of critical resources in small islands from a socio-metabolic risk perspective

Methodology details for the elaboration of Chapter 3 – The resource (inter)dependency of critical resources in small islands.

Abstract: This Appendix A provides underlying data in tabular form for Figure 3, Figure 4, and Figure 5 of Chapter 3.

Table A - 1 - Water-Energy-Food Performance Indicators for 14 Caribbean SIDS

		Availability (m^3/cap/yr)		**Access (%)**		**Consumption (m^3/cap/yr)**		**Self-sufficiency (%)**	
WATER	**SIDS**	**2000**	**2017**	**2000**	**2017**	**2000**	**2017**	**2000**	**2017**
	Antigua and Barbuda	688	545	90	92	111	121	100	100
	Aruba	0	0	96	98	121	120	0	0
	Barbados	295	279	94	98	298	283	100	100
	Cuba	3,430	3,362	63	70	468	614	100	100
	Dominica	2,852	2,799	79	87	238	280	100	100
	Dominican Republic	2,779	2,235	84	90	574	681	100	100
	Grenada	1,946	1,804	92	94	97	127	100	100
	Haiti	1,540	1,185	36	50	152	132	89	93
	Jamaica	4,087	3,704	88	89	306	464	100	100
	St. Kitts and Nevis	543	461	92	95	147	300	100	100
	St. Lucia	1,924	1,658	85	93	274	282	100	100
	St. Vincent and the Grenadines	926	911	82	91	93	77	100	100
	The Bahamas	2,339	1,834	93	97	94	92	100	100
	Trinidad & Tobago	3,023	2,774	91	96	248	277	100	100
	Averages	**1,884**	**1,682**	**83**	**89**	**230**	**275**	**92**	**92**
		Availability (GJ/cap/yr)		**Access (%)**		**Consumption (GJ/cap/yr)**		**Self-sufficiency (%)**	
ENERGY		**2000**	**2017**	**2000**	**2017**	**2000**	**2017**	**2000**	**2017**
	Antigua and Barbuda	179	142	100	100	101	114	0	1
	Aruba	12	11	92	100	175	180	0	8
	Barbados	277	79	100	100	92	89	19	12
	Cuba	560	315	88	100	36	37	35	41
	Dominica	178	174	81	100	27	53	18	7
	Dominican Republic	3	2	89	100	37	34	3	8
	Grenada	146	135	86	96	30	40	0	1
	Haiti	4	3	34	44	3	5	12	2
	Jamaica	12	11	85	100	59	46	2	5
	St. Kitts and Nevis	959	812	94	100	63	65	0	2
	St. Lucia	50	43	88	99	34	38	0	0
	St. Vincent and the Grenadines	279	273	74	100	23	27	11	9
	The Bahamas	38	30	100	100	199	117	0	0
	Trinidad & Tobago	34,188	12,670	80	100	367	690	100	100
	Averages	**207***	**156***	**85**	**96**	**89**	**110**	**14**	**14**
		Availability (kg/cap/yr)		**Access (%)**		**Consumption (kcal/cap/day)**		**Self-sufficiency (%)**	
FOOD	**SIDS**	**2000**	**2017**	**2000**	**2017**	**2000**	**2017**	**2000**	**2017**
	Antigua and Barbuda	624	610	58	86	2,149	2,429	35	23
	Aruba	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
	Barbados	640	603	95	96	2,803	2,896	85	53
	Cuba	757	848	95	98	3,030	3,409	100	92
	Dominica	1,063	1,013	95	94	3,065	2,945	100	85

	Dominican Republic	502	791	72	91	2,218	2,856	88	89
	Grenada	558	596	69	81	2,221	2,404	56	62
	Haiti	381	422	45	55	1,959	2,163	80	75
	Jamaica	686	675	93	91	2,725	2,754	85	74
	St. Kitts and Nevis	614	542	82	90	2,516	2,517	94	77
	St. Lucia	719	558	88	88	2,706	2,658	81	64
	St. Vincent and the Grenadines	525	679	83	94	2,499	2,962	100	78
	The Bahamas	897	638	91	90	2,781	2,043	37	50
	Trinidad & Tobago	544	526	88	93	2,776	3,039	78	44
	Averages	**655**	**654**	**81**	**88**	**2,573**	**2,698**	**78**	**67**

**Trinidad & Tobago, as a special case, was excluded on the calculations of averages of energy availability in the region due to it being several orders of magnitude higher than the rest of the countries.*

Appendix B - The significance of resource-use patterns and socio-metabolic risks to build resilience in small islands

Methodology details for the elaboration of Chapter 4 – The significance of resource-use patterns and socio-metabolic risks to build resilience in small islands

Abstract: This Appendix B provides extra information of Chapter 4 about data sources for DE, Imports and Exports, and estimates of outflows (municipal solid waste, demolition and discard waste, ash content from combustion, manure production), and provides an overview of data quality for the main indicators. Additionally, it provides figures of disaggregated masses of flows for the mass balance and provides a comparison of waste generation across the Caribbean SIDS. Moreover, it provides tables with socio-metabolic indicators utilized for the mass balance and that were utilized to elaborate Figure 8 in Chapter 4.

Table B - 1 - Main data sources for Domestic Extraction

Domestic extraction	Main data sources	Methodological details
Biomass	Food and Agriculture Organization of the United Nations (FAO, 2021a, 2021b)	FAO Metadata technical details. Available at source. (FAO, 2021a, 2021b)
Metals	Brown et al., (2021); UNEP & IRP, (2022)	Brown et al. (2021), p.iv; GLORIA Technical Documentation. (Brown et al., 2021; Geschke, 2021, p. 1)
Non-metallic minerals	Brown et al., (2021); UNEP & IRP, (2022)	Brown et al. (2021), p.iv; GLORIA Technical Documentation. (Brown et al., 2021; Geschke, 2021, p. 1)
Fossil-energy materials/carriers	Food and Agriculture Organization of the United Nations (2021b); U.S. Energy Information Administration (2021). (EIA, 2021; FAO, 2021a, 2021b)	FAO Metadata technical details. U.S. Energy Information Administration technical details. Available at source. (EIA, 2021; FAO, 2021a, 2021b)
Other	Not applicable since only domestic extraction of raw materials was accounted for	Not applicable

Table B - 2 - Main data sources for Imports and Exports

Imports/exports	HS code chapters from the UN Comtrade database	Other sources	Methodological details
Biomass	1–21, 23, 24, 44 (United Nations Statistics Division, 2018)	Food and Agriculture Organization of the United Nations (FAO, 2021a, 2021b)	Bahamas Metadata on International Merchandise Trade Statistics. FAO Metadata technical details. Available at source. (FAO, 2021a, 2021b)
Metals	26, 72–83 (United Nations Statistics Division, 2018)	N/A	Bahamas Metadata on International Merchandise Trade Statistics. Available at source
Non-metallic minerals	25, 31 (United Nations Statistics Division, 2018)	N/A	Bahamas Metadata on International Merchandise Trade Statistics. Available at source
Fossil-energy materials/carriers	27, 44 (United Nations Statistics Division, 2018)	Food and Agriculture Organization of the United Nations (2021b); U.S. Energy Information Administration (2021). (EIA, 2021; FAO, 2021a, 2021b)	FAO Metadata technical details. U.S. Energy Information Administration technical details. Available at source
Other	22, 28–30, 32–43, 45–71, 84–97 (United Nations Statistics Division, 2018)	N/A	Bahamas Metadata on International Merchandise Trade Statistics. Available at source

Table B - 3 - Municipal solid Waste composition shares for The Bahamas. Source: Kaza et al., (2018). Methodological details: Kaza et al., (2018, p.9)

Waste type	Share [%]	Total MSW [kt]	Category
Food and green	52	132.6	Biomass
Glass	4	10.2	Non-metallic mineral
Metal	3	7.65	Metal
Paper/cardboard	13	33.15	Biomass
Plastic	12	30.6	Other
Rubber and leather	0.5	1.275	Other
Wood	0.5	1.275	Biomass
Other	15	38.25	Other
Totals	**100**	**255**	

Table B - 4 - Demolition & Discard Waste Composition Shares of South Florida Based on the US Building Code. Taken as Valid for the Building Code of The Bahamas. Source: U.S. Environmental Protection Agency, (2016)

Demolition debris	Totals [%]	Total Demolition & Discard waste [kt]	Category
Concrete	70	67.8	Non-metallic minerals
Asphalt concrete	15	14.5	Non-metallic minerals
Wood	7	6.8	Biomass
Asphalt shingles	2.5	2.4	Non-metallic minerals
Brick/clay	2.33	2.3	Non-metallic minerals
Drywall/plaster	2.04	2.0	Non-metallic minerals
Steel	0.85	0.82	Metal
Totals	**100**	**96.9**	

Table B - 5 - eUse of Materials and Ash Content from Combustion Processes. Source: (Kofman, 2016; Kuyumcu, 2019; Sarkar et al., 2011)

Material	Material weight [kt]	Ash content by weight [%]	Ashes weight [kt]
Hydrocarbons	772	0.03–0.07	54
Coal	2.032813	4–16	0.32525
Woodfuel	59.6	6–10	5.96
Totals	**833.6**		**60.28**

Table B - 6 - Livestock Numbers and Total Manure Production Per Year in The Bahamas for the Year 2018. Source: European Commission, (2018); World Organization for Animal Health, (2021)

Livestock	Heads	Manure production per day (kg)	Dry matter of manure %	Total manure production per year (kt)
Cattle	9295	70	0.085	20.2
Chicken	3036000	0.2	0.15	33.2
Goat	9200	28	0.085	8
Horse	74	7	0.07	0
Pig	47000	26	0.028	1.3
Totals				**62.7**

Table B - 7 - Recycled Materials in The Bahamas (2018). Source: L. Smith, (2014); WasteNot Limited (2021)

Materials	Volume [t/yr]	Main category
Carboard	236	Biomass
Oil (biodiesel)	86	Biomass
Batteries	139	Other
Green waste (garden/compost)	6,480	Biomass
Aluminum Cans	0.22	Metals
Totals	**6,941.22**	

Table B - 8 - Overview of data quality for the main indicators of the ew-MFA in The Bahamas for 2018 based on an adapted "pedigree matrix"

	Indicator score	***Reliability***	***Completeness***	***Temporal correlation***	***Geographical correlation***	***Access***	***Additional steps***
Scale indicators	**Input**						
	DE	2	1	1	1	1	2
	IMP	2	1	1	1	1	2
	Use						
	DMC	3	1	1	1	1	2
	SM	4	4	2	1	5	2
	Output						
	EXP	2	1	1	1	1	2
	C&D waste	4	4	3	4	4	3
	MSW	4	4	3	2	2	3

Note: The scores are "semi-quantitative" and serve only as identification numbers. They should not be aggregated, but rather only be used as a reference to better understand the quality of the different data sources

Table B - 9 - key: Adapted pedigree matrix data quality indicators. Source: Allesch & Rechberger, (2018)

Indicator Score	***1***	***2***	***3***	***4***	***5***
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate or unknown origin
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Time period is equal to the period of study	Less than one year of difference to year of study	Less than three years of difference to year of study	Less than five years of difference to year of study	Age of data unknown or more than five years of difference
Geographical correlation	Data from area under study	Average date from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Access	Publicly and readily available data	Data are not publicly available but can be easily obtained by anyone	Specific effort required to obtain data (e.g. only through formal requests, granted on a per-case basis)	Data are only accessible to very specific users (e.g. government or partner organizations)	Data are only accessible to the organization holding the data
Additional steps	No additional steps involved	Simple calculations or conversion required (easy to repeat)	Simple calculations or conversion required (difficult to repeat)	Complex calculations or conversion required (easy to repeat)	Complex calculations or conversion required (difficult to repeat)

Table B - 10 - Overview of Scale indicators for the ew-MFA main material categories and sub-categories in the Bahamas for 2018. Units in [kT/yr]

Scale indicators	***Fossil fuels***		***Biomass***	***Metals***	***Non-metallic minerals***				***Other***	***Total***
Main commodity	Spirits	Petroleum oils			Sand, gravel	Cement	Salt	Other non-metallic minerals		
Input										
DE	0	0	252	0	361	0	854	45	0	1,512
IMP	533	474	349	71	0	230	1	13	438	2,109
DMI	533	474	601	71	45	591	1	867	438	3,621
Use										
DMC	533	239	588	41	360	230	1	57	293	2,342
PM	533	239	595	41	360	230	1	57	293	2,349
SM	0	0	7	0	0	0	0	0	0	7
eUse	533	239	445	0	0	0	0	0	0	1,217
mUse	0	0	150	41	360	230	1	57	293	1,132
Stocks										
GAS	0	0	116	33	360	230	0	47	223	1,009
NAS	0	0	105	32	246	211	0	37	223	854
Output										
EXP	0	235	13	30	1	0	854	1	145	1,279
C&D waste	0	0	11	1	114	19	0	10	0	155
IntOut	533	239	490	9	114	19	1	20	70	1,495
DPO	533	239	483	9	114	19	0	20	70	1,487
DPOe	496	222	243	0	0	0	0	0	0	961
DPOw	37	17	240	9	114	19	0	20	70	526

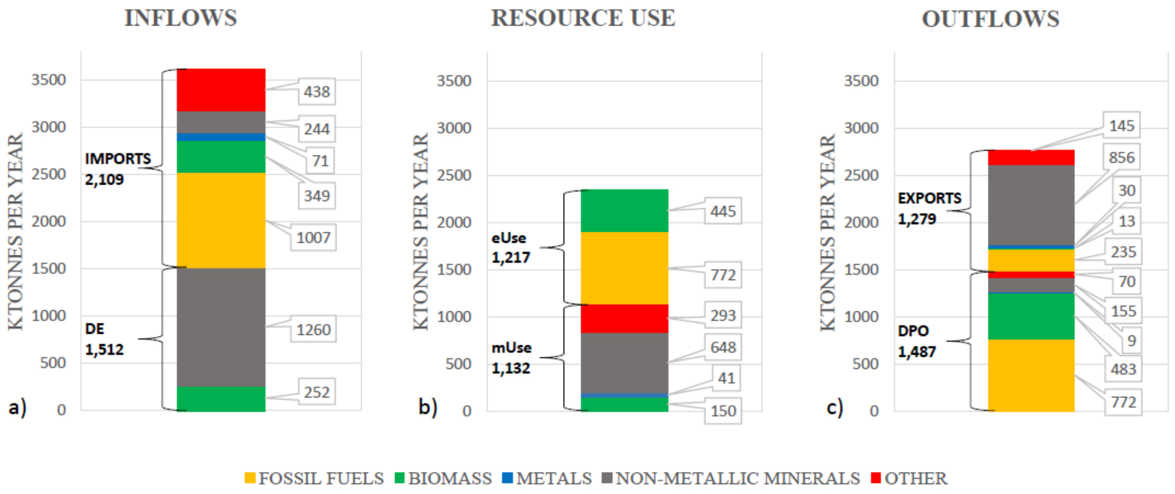


Figure B - 1 - Disaggregated masses of flows by main material categories for selected scale indicators of The Bahamas ew-MFA in 2018

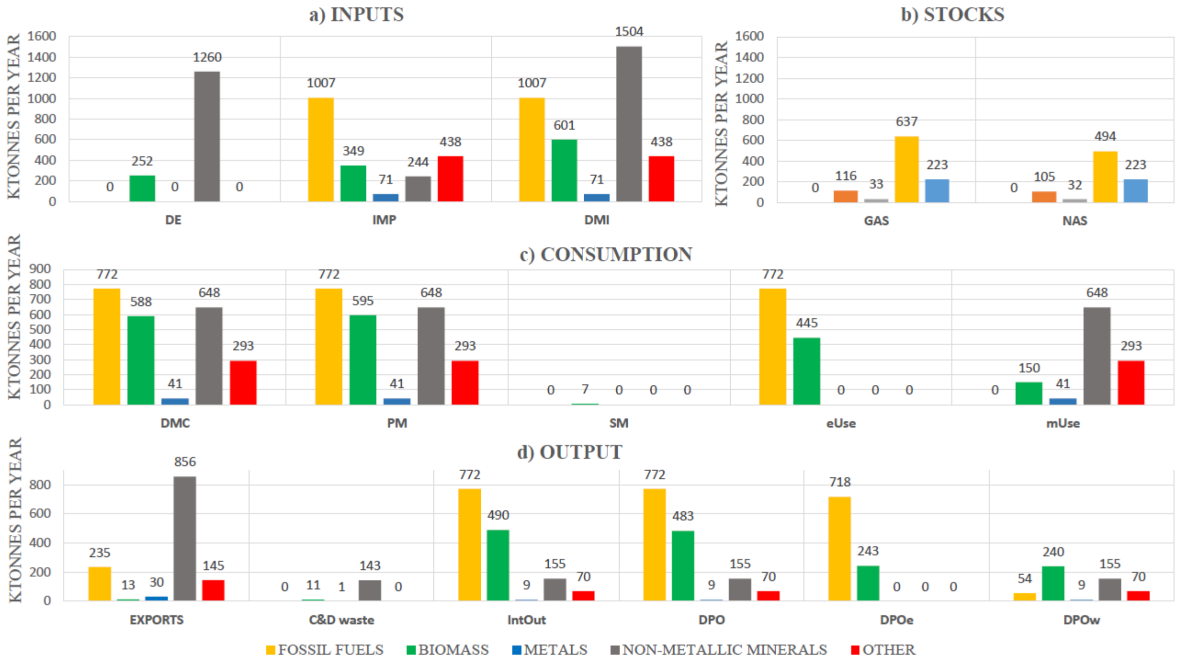


Figure B - 2 - Disaggregated masses of flows by main material categories for all scale indicators of The Bahamas ew-MFA in 2018

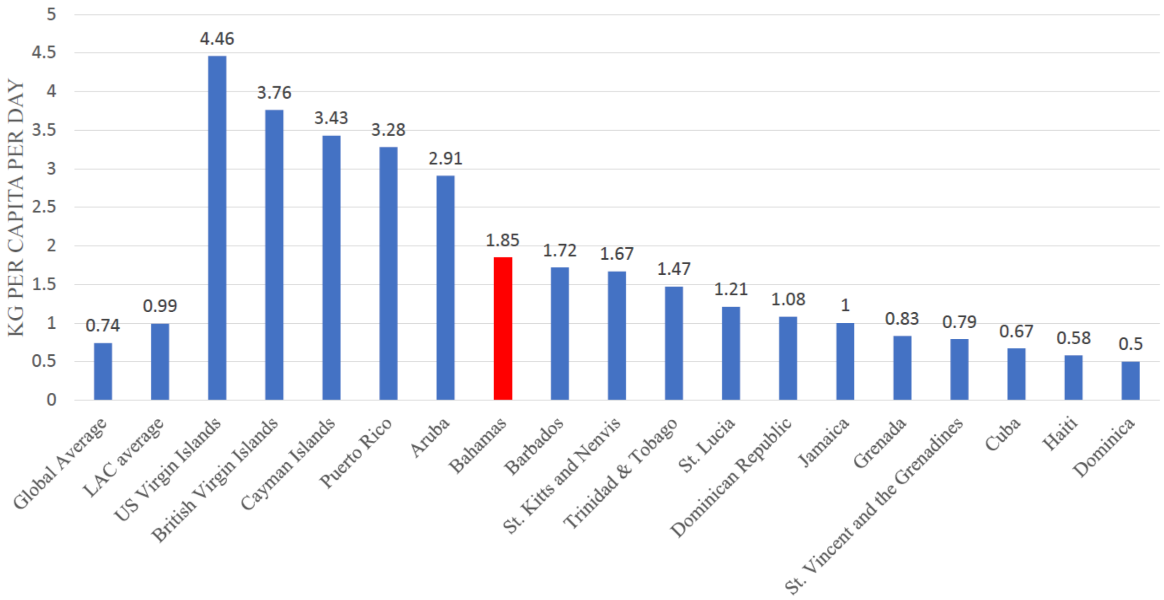


Figure B - 3 - Municipal Solid Waste Generation Rates in selected Caribbean SIDS in 2016. Source: Kaza et al., (2018)

Appendix C - The role of critical infrastructure on sustainability and resilience in small islands

Methodology details for the elaboration of Chapter 5 - The role of critical infrastructure on sustainability and resilience in small islands.

Abstract: This Appendix C provides extra information of Chapter 5 about the approach taken to quantify current and future material stocks in The Bahamas for the year 2021, as well as additional information about steps to account for the impacts of sea-level rise on material stocks. Furthermore, it presents a methodology for a rough estimation of potential future neighborhood development areas across the country through the utilization of OpenStreetMap (OSM) data. Additionally, it provides a brief step-by-step tutorial on how to download, process, and work with historical whole-planet OpenStreetMap (OSM) files through the utilization of specific software as a way to aid in the process of spatial analysis of historical data for a specific zone in the world. Additionally, it provides additional data on figures and tables for Chapter 5.

1.- Introduction

This supplementary data provides more insight into the data sources, methodology and further analysis that was followed and executed for the economy-wide material flow analysis, future stocks quantifications, as well as simulations of infrastructure potentially impacted by different sea-level rise (SLR) scenarios. Section 2 accounts for the methods utilized to estimate the material stocks (MS) of buildings and roads, and is followed by Section 3, which accounts for the methodology utilized for the estimation of future MS for both buildings and roads. Section 4 presents the methodology followed to account for potential effects on stock under different sea level rise (SLR) scenarios.

2.- Material stocks of buildings and roads: Stocks of buildings

The general approach to calculate MS of buildings was to categorize the building inventory in distinctive use-types or typologies, calculate the gross floor area, apply material intensities that correspond to each category (residential, commercial, industrial, government, and other), and then calculate the total MS for 4 main construction materials, which are: aggregate, concrete, timber, and steel.

The November 2021 OpenStreetMap (OSM) GIS building footprint shapefile was the base utilized for the estimations of MS. This shapefile was extracted through the Humanitarian Data Exchange project (Humanitarian OpenStreetMap Team, 2021a) and worked with it under the ArcGIS Pro 2.8.3 software. By visually comparing current satellite imagery from Google Earth (Google Earth Pro®, 2021) with the OSM building footprint dataset, it was revealed that complete data on footprints was missing for only certain sections of the districts in the country, such as in west New Providence, Black Point, Central Abaco, Exuma island, and Cat island. Facing this situation, the analysis utilized only the building footprints already present in the November 2021 building footprint shapefile.

The first step to begin with the classification of the building inventory was to explore the content of the OSM shapefile layer on ArcGIS to see existing and missing information. As seen in Table C - 1, from the shapefile's Table of Attributes, it was found the following field names:

Table C - 1 - Brief description of field names within the November 2021 building footprints OSM shapefile layer of The Bahamas. Source: Humanitarian OpenStreetMap Team, (2021a)

Field Name	Brief Description
Addrcity	The name of the city as given in postal addresses of the building/area
Source	Used to indicate the source of some information
Office	Used to map an office, a place predominantly providing services
Addrstreet	Street name
Building	Used to mark a given object as a building
Buildingma	Used to indicate the main material of which the given building is made of
Addrhousen	Used to indicate the house number
Buildingle	Used for marking the number of above-ground levels of a building
Addrfull	Full address of the building
Name	Used to indicate the name of the feature

Based on the information seen above, one could extract data on building typologies through browsing the fields "building", "office", and "name". The "building" field contains almost 60 values that fall under the five main building typologies to be analyzed as seen in Table C - 2.

Table C - 2 - Main use-type of building footprints within the OSM shapefile layer of The Bahamas. The tags under the "building" field of the shapefile layer were classified as shown in this table.

Main building typology	Residential	Commercial	Industrial	Government	Other
Classification of tags under the "building" field	Apartments	Central_office	Industrial	Civic	Abandoned
	Boathouse	Commercial	Barn	College	Bunker
	Bungalow	Gazebo	Farm	Government	Construction
	Cabin	Kiosk	Farm_auxiliary	Immigration	Container
	Detached	Mall	Greenhouse	School	Lighthouse
	Dormitory	Office	Stable	Public	Roof
	House	Retail	Silo	Toilets	Ruins
	Residential	Supermarket	Hangar	Transport	Carpot
	Semidetached	Warehouse	Hut	Chapel	Garage
	Terrace	Hotel	Shed	Church	No
		Grandstand	Storage_tank	Parish	
		Sports_centre		Yes:church	
		Sports_hall			

	Stadium
***Unclassified: "yes" tag**	

The “yes” building were not included in neither of the main typologies as of this point. On the same way as in the “building” field, the “yes” buildings will be accounted for through filtering of the “office” and “name” fields as indicated in the following sections.

To be able to differentiate the “yes” buildings from the “building” field, the methodology advices to first isolated the unclassified “yes” buildings into an independent dataset file. Once this was done, within this selection the study proceeded to analyze the “office” field, which contained 15 values with tags that could help further allocate buildings into the main typologies (see Table C - 3).

Table C - 3 - Sub-classification of building footprint within the OSM shapefile layer of The Bahamas. The tags under the "office" field of the shapefile layer were classified as shown in this table

Main building typology	**Commercial**		**Government**
Classification of tags under the “office” field	Architect	Insurance	Government
	Association	Lawyer	
	Company	Ngo	
	Estate_Agent	Pool_Construction	
	Finance	Security	
	Financial	Telecommunications	
	General_Contractor	Yes	
***Unclassified: Empty tag under "office" field**			

Next, the study further classified the empty tags under the “office” field by first creating a new shapefile layer with only the empty tags. Then followed the analysis of the “name” field, which contained more than 700 values. Keywords search within the “name” field to filter those values were included (see Table C - 4).

Table C - 4 - Sub-classification of building footprint within the OSM shapefile layer of The Bahamas. The empty tags under the "office" field of the shapefile layer were classified utilizing the keywords shown in this table.

Main building typology	**Government**			**Commercial**
Keywords of tags under the “name” field	Health	Museum	Power Tower	Hotel
	Academy	CIBC	Credit Union	Resort
	Office	City	Hospital	Inn
	Airport	Terminal	Royal	Supermarket
	Church	Medicine	Salvation	Cinemas
	Archaeological	Post Office	Scotiabank	
	Customs Hq	Ministry	Salaried Workers	
	Bank	Chapel	Western Air	
	Government	Society	Auditorium	
	Historical	Immigration	Library	
	Court	Medical	Western Air	
	Temple	Clinic	Auditorium	
	Cancer	MediCentre	Library	
	Museum	Police		
***Unclassified - empty tag under "name" field**				

Once more, the empty tags under the “name” field were classified by creating a new shapefile with only the “name” empty tags. Then, the “buildingle” field was utilized. The values of this field ranged from 0 to 13 stories. An assumption was made that the buildings with “buildingle” field with 4 or more stories were classified as “commercial”.

Image interpretation was manually performed by zooming into the building footprint from OSM and by comparing the OSM dataset with external mapping platforms, specifically aerial imagery (Google Earth Pro®, 2021) and tags from google maps. All the remaining unclassified buildings that had levels equal or less than 3 levels were sorted by building gross floor area (GFA) in m^2. To calculate the GFA of each individual building “*b*”, first was calculated the individual building footprint $area_{(b)}$ and then multiplied it with its corresponding number of $stories_{(b)}$ as seen in Equation C - 1.

Equation C - 10

$$GFA_{(b)} = Building\ footprint\ area_{(b)} \times Number\ of\ floor\ stories_{(b)}$$

A classification of only the top 100 buildings in terms of GFA was performed. By a visual inspection, some of the building footprints surrounding the 100 buildings which were smaller in size, but that were in very close proximity to the larger building, were assumed to acquire the same use-type designation as the larger building which fell in each of the main use-type categories.

To proceed with the final classification, the study focused on residential areas, such as the ones east of New Providence island, and within the City of Freeport. "Residential" buildings were classified as all buildings with GFA larger than 80 m^2 and smaller than 350 m^2. 80 m^2 was selected as minimum residential GFA based on the restrictive covenants from the Grand Bahama Development Company (GBDC, 2022), which establishes a built area of less than 1,000 sqft per residential type units. Through a spatial analysis of samples of identified residential zones, one could notice that the residential building GFA’s ranged between 80 m^2 to 350 m^2. For the calculations, the study assumed a max value of 350 m^2 for residential buildings. Buildings larger than 350 m^2 were classified as "commercial" buildings, while the ones with areas smaller than 80 m^2 were classified as "other" (see Table C - 5).

Table C - 5 - Final classification of the November 2021 building footprint OSM shapefile layer by number of building footprints in The Bahamas.

Main use-type of Building Footprint	# of footprints
Residential	84,360
Commercial	22,723
Industrial	559
Government	754
Other	8,650
TOTAL	**117,046**

Currently, no building material intensity data exists for The Bahamas. To understand the building MI in The Bahamas, an exploration of the census of population and housing (Government of The Bahamas, 2012), as well as household expenditure surveys was performed (Government of The Bahamas, 2016a). The study also consulted previous publications with information on building typologies in other Caribbean SIDS, namely Grenada (Symmes et al., 2019) and Antigua & Barbuda (Bradshaw et al., 2020).

In Grenada, a few older traditional buildings are composed of brick and stone, with tile roofs. In recent decades, there has been a change in typical building structures. As new construction materials became more available and cheaper (such as 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 the case of Antigua & 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. Moreover, many of the oldest small buildings and homes are fully timber-framed and timber-clad. On the other hand, 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 & 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 based on a structure of concrete block (80% for all outer walls of dwellings), with poured concrete slabs and concrete foundations (90% of all floors) (see Table C - 6). The most common roofing materials are asphalt shingles (90%) and corrugated metal sheets (4%) (Government of The Bahamas, 2016). This construction style for dwellings can be largely seen across New Providence and Grand Bahama, and with slightly lower extents in the Family Islands. Wood and timber constructions as main structural components are in use as well, but with lower shares (ECLAC, 2020). Considering that The Bahamas's building typologies share more similarities with Grenada's buildings than with Antigua & Barbuda (higher utilization of heavier concrete material and smaller share of lighter timber material), the study opted to utilize the MIs described in Symmes et al. (2019). Table C - 7 shows MIs for buildings, as well as use-types considered for each building typology.

Table C - 6 - The Bahamas' residential building structure composition. Source: Government of The Bahamas, (2016).

Residential structure	**Outer walls %**	**Floors %**	**Averages % (rounded to nearest 5%)**
Concrete, Blocks, or Slabs	80.6	93	85
Timber	12.1	5	10
Combination	7.3	2	5

Table C - 7 - Material intensities allocated for each building type, as well as allocation of building main use-types. Source: Symmes et al., (2019)

Buildings	**Aggregate**	**Timber**	**Concrete**	**Steel**	**Element considered**
Concrete structure (kg/m^2)					Residential (85%); Commercial; Government
Foundation - Strip footings	135	0	225	5	
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**	**1,645**	**36**	
Timber structure (kg/m^2)					Residential (10%) Other
Foundation - Pad footings	45	0	45	1	
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)					Residential (5%)
Foundation - Strip footings	135	0	225	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**	**1,125**	**35**	
Steel structure (kg/m^2)					Industrial Airport buildings Seaport buildings
Foundation - Strip footings	135	0	225	5	
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**	**1,645**	**325**	

Material stock *"MS"* was then calculated for each of the main material categories *"m"* and for each of the individual buildings "*b*" by multiplying the *"$GFA_{(b)}$"* by its corresponding *"$MI_{(m)}$"*.

Equation C - 11

$$MS_{(b,m)} = GFA_{(b)} \times MI_{(m)}$$

Total material stock *"MS_{total}"* per main material category and for a given building *"$GFA_{(b)}$"* was calculated by using the following equation:

Equation C - 12

$$MS_{total} = \sum MS_{(b,m)} = MS\ Aggregate_{(b,m)} + MS\ Timber_{(b,m)} + MS\ Concrete_{(b,m)} + MS\ Steel_{(b,m)}$$

To calculate the total MS per building use-type, Equation C - 3 is applied for each of the five use-type categories.

Material stocks of buildings and roads: Stocks of transport

To account for transport related stocks, the study considered the paved share of the road network of the country, airports (buildings and runways), as well as the main seaports (buildings and cargo platforms of larger seaports). In a similar way to the Stocks of Buildings, the general approach to calculate transport MS was to categorize the inventory in distinctive use-types, calculate the area (buildings and cargo areas) or length (roads and runways) of each of these, apply material intensities that correspond to each use-type and then calculate the total MS for the main construction materials, which are: aggregate, concrete, steel, asphalt, and base material.

During the transport stocks classification process, the study worked with three GIS shapefile layers in parallel. The first shapefile was the same shapefile containing most of the building footprints of The Bahamas, from which the ones corresponding to seaports and airports were filtered. This selection of Transport buildings was based on building proximity to existing seaports and airports facilities. The geographic position of these facilities throughout The Bahamas was sourced from online databases with contents on Airports (OurAirports, 2022) and Seaports (SeaRates, 2022) georeferenced locations. Satellite imagery (Google Earth Pro®, 2021) was utilized to visually cross-check facility locations with building footprints, and a manual selection of surrounding building footprints was performed for both seaports and airports. Then, the "industrial" typology MI was applied to those selected buildings to calculate the corresponding building MS.

The second shapefile layer is a November 2021 roads network file extracted from OSM through the Humanitarian OpenStreetMap Team (HOTOSM) (Humanitarian OpenStreetMap Team, 2021b), while the third OSM shapefile was another November 2021 roads network file extracted through Geofabrik GmbH (Geofabrik GmbH, 2021). The study utilized both files under the ArcGIS Pro 2.8.3 software. By visually comparing current satellite imagery from Google Earth with the OSM road network dataset, it was found that the network was practically complete in the whole country. By reviewing the information contained in the Table of Attributes of the roads network OSM shapefile layers, the following field names were found (see Table C - 8).

Table C - 8 - Brief description of field names within the November 2021 roads network OSM shapefile layers of The Bahamas. Source: Geofabrik GmbH, (2021); Humanitarian OpenStreetMap Team, (2021b)

	Field Name	Brief Description
HOTOSM extract	Highway	Is the main tag used for identifying any kind of road, street or path
	Name	This tag is set to the primary name of the feature in the real world
	Oneway	Used to indicate the access restriction on highways and other linear features for vehicles as appropriate
	Layer	Used to mark the vertical relationship between two intersecting features
	Bridge	Property to describe that a way is on a bridge
	Source	Used to indicate the source of some information (i.e. meta data) added to OpenStreetMap
	Surface	Used to provide additional information about the physical surface of roads/footpaths and some other features, particularly regarding material composition and/or structure
	Lanes	Tag used to indicate how many traffic lanes there are on a highway or other features
	Smoothness	Provides a classification scheme regarding the physical usability of a way for wheeled vehicles, particularly regarding surface regularity/flatness
	Width	Describes the actual width of a way or other feature
Geofabrik extract	Fclass	In the same way as "highway", this tag is used for identifying any kind of road, street or path
	Name	This tag is set to the primary name of the feature in the real world
	Oneway	Used to indicate the access restriction on highways and other linear features for vehicles as appropriate
	Layer	Used to mark the vertical relationship between two intersecting features
	Bridge	Property to describe that a way is on a bridge
	Ref	stands for "reference" and is used for reference numbers or codes
	Maxspeed	Is used on ways to define the maximum legal speed limit for general traffic on a particular road, railway or waterway
	Tunnel	Is used for roads, railway line, canals etc. that run in a tunnel

By performing a quick spatial analysis on total roads length, it was found that the HOTOSM shapefile contained roughly 11,350 km of roads, while the Geofabrik shapefile contained around 11,320 km of roads. The records of both road shapefiles matched closely, but some unique fields (three unique fields for Geofabrik GmbH and five for HOTOSM) were found. Moreover, the analysis found similarities between data on roads classifications that can be extracted from the field names of "highway" from the HOTOSM file and "fclass" from the Geofabrik file (see Table C - 9).

Table C - 9 - Comparison between the two OSM road shapefiles and the tags under their respective field names. Source: Geofabrik GmbH, (2021); Humanitarian OpenStreetMap Team, (2021b)

	Field Name: Highway	**Brief Description**
HOTOSM extract	Bridleway	For horse riders. Pedestrians are usually also permitted, cyclists may be permitted depending on local rules/laws
	Construction	For roads under construction
	Cycleway	Path usable by cyclists
	Footway	paths mainly for walkers
	Living_Street	residential streets
	Path	A non-specific path
	Pedestrian	For roads used mainly/exclusively for pedestrians in shopping and some residential areas which may allow access by motorised vehicles only for very limited periods of the day
	Primary	Roads in a country's system that often link larger towns
	Primary_Link	The link roads (sliproads/ramps) leading to/from a primary road from/to a primary road or lower class highway
	Residential	Roads which serve as an access to housing, without function of connecting settlements. Often lined with housing
	Road	A road/way/street/motorway/etc. of unknown type
	Secondary	Roads in a country's system that often link towns
	Secondary_Link	The link roads (sliproads/ramps) leading to/from a secondary road from/to a secondary road or lower class highway
	Service	For access roads to, or within an industrial estate, camp site, business park, car park, alleys
	Steps	For flights of steps (stairs) on footways
	Tertiary	Roads in a country's system that often link smaller towns and villages
	Tertiary_Link	The link roads (sliproads/ramps) leading to/from a tertiary road from/to a tertiary road or lower class highway.
	Track	A track provides a route that is separated from traffic
	Unclassified	minor roads of a lower classification than tertiary, but which serve a purpose other than access to properties
Geofabrik extract	**Field Name: Fclass**	
	Bridleway	For horse riders. Pedestrians are usually also permitted, cyclists may be permitted depending on local rules/laws
	Cycleway	Path usable by cyclists
	Footway	paths mainly for walkers
	Living_Street	residential streets
	Path	A non-specific path
	Pedestrian	For roads used mainly/exclusively for pedestrians in shopping and some residential areas which may allow access by motorised vehicles only for very limited periods of the day
	Primary	Roads in a country's system that often link larger towns
	Primary_Link	The link roads (sliproads/ramps) leading to/from a primary road from/to a primary road or lower class highway
	Residential	Roads which serve as an access to housing, without function of connecting settlements. Often lined with housing
	Secondary	Roads in a country's system that often link towns
	Secondary_Link	The link roads (sliproads/ramps) leading to/from a secondary road from/to a secondary road or lower class highway
	Service	For access roads to, or within an industrial estate, camp site, business park, car park, alleys, etc
	Steps	For flights of steps (stairs) on footways
	Tertiary	Roads in a country's system that often link smaller towns and villages
	Tertiary_Link	The link roads (sliproads/ramps) leading to/from a tertiary road from/to a tertiary road or lower class highway.
	Track	A track provides a route that is separated from traffic
	Track_Grade1	To describe the quality of the surface
	Track_Grade2	To describe the quality of the surface
	Track_Grade3	To describe the quality of the surface
	Track_Grade4	To describe the quality of the surface
	Track_Grade5	To describe the quality of the surface

Unknown	Unknown type of road

From Table C - 9, one can see that both field names "highway" and "fclass" could be used to determine the type of road in the network. While the HOTOSM shapefile has 18 tags for the classification of roads, the Geofrabrik shapefile has 22. Moreover, the HOTOSM shapefile has the field name “surface”, which also gives some indication of material composition for the roads. As such, the study decided to utilize the HOTOSM shapefile as the first criteria for the analysis of roads stocks.

Next, the roads were assigned a value of “paved” or “unpaved” depending on the classification of “highway” from the HOTOSM shapefile (see Table C - 10).

Table C - 10 - Partial classification of roads based on field name “highway” from The Bahamas 2021 HOTOSM roads shapefile.

Paved		**Unpaved**	
Tag	**Length (Km)**	**Tag**	**Length (Km)**
Living_Street	0.06	Bridleway	0.8
Primary	201	Construction	3.5
Primary_Link	1.6	Cycleway	1.2
Residential	2,800	Footway	164.8
Secondary	640	Path	269.9
Secondary_Link	0.5	Pedestrian	1.7
Tertiary	910	Steps	0.6
Tertiary_Link	0.6	Track	4,137.5
Service	960		
Road	0.14		
TOTAL (partial)	**5,530**	**TOTAL (partial)**	**4,579.4**
Unclassified = 1,244 Km			

In Table C - 10 there was a tag of “unclassified” roads under the “highway” field. To allocate this into one of the two categories of paved or unpaved, the study filtered those “unclassified” tags by selecting the roads with “asphalt”, “concrete”, and “paved” tags under the “surface” field. These three tags were assumed to be “paved” (see Table C - 11).

Table C - 11 - Partial classification of roads based on “unclassified” tag under field name “highway” from The Bahamas 2021 HOTOSM roads shapefile. Selection of Paved or Unpaved was based on the field “surface”.

Paved		**Unpaved**	
Tag	**Length (Km)**	**Tag**	**Length (Km)**
Asphalt	165.9	Compacted	3.7
Concrete	0.09	Dirt	23.6
Paved	1.2	Gravel	3.3
		Ground	1.1
		Paving_stones	0.0
		Sand	5.2
		Unpaved	79.8
TOTAL (partial)	**167.2**	**TOTAL (partial)**	**116.7**

NULL = 960 km

For the remaining empty, or "NULL" records, an assumption was made that the roads that had a name were considered to be "paved", while the ones that did not had a name were considered as "unpaved". "Named" roads (paved) amounted to around 183 km, while "not named" roads (unpaved) amounted to around 777 km.

Summarizing the findings from the exploration and filtering of the HOTOSM roads shapefile is Table C - 12. The "*Unclassified" tags correspond to the sum of partial lengths from Table C - 11 plus the "Named" or "Not named" road lengths as previously mentioned.

Table C - 12 - Final classification of paved and unpaved roads length from The Bahamas 2021 HOTOSM roads shapefile

Paved		**Unpaved**	
Tag	**Length (Km)**	**Tag**	**Length (Km)**
Living_Street	0.06	Bridleway	0.8
Primary	201	Construction	3.5
Primary_Link	1.6	Cycleway	1.2
Residential	2,800	Footway	164.8
Secondary	640	Path	269.9
Secondary_Link	0.5	Pedestrian	1.7
Tertiary	910	Steps	0.6
Tertiary_Link	0.6	Track	4,137.5
Service	960	*Unclassified	893.8
Road	0.14		
*Unclassified	350.4		
TOTAL	**5,881**	**TOTAL**	**5,473.8**

For the road network, the Design and Construction Guidelines and Plan Preparation Manual for Subdivisions in The Bahamas (Government of The Bahamas, 2004) contains specific designs for paved roads, which are influenced by the speed limit and location of the roads. The study made a comparative analysis between the design guidelines and the roads classification speed limits from the Geofabrik shapefile, and filtering process for paved roads from the HOTOSM roads shapefile. Then, the study allocated the distinct roadway types by design to the existing roadway types from the shapefile, as seen in Table C - 13.

Table C - 13 - Correlation between the roads OSM classification and The Bahamas' Design guidelines classification for paved roads. Source: Geofabrik GmbH, (2021); Government of The Bahamas, (2004); Humanitarian OpenStreetMap Team, (2021b)

Roadway Type by Design Guidelines	**Max Speed (Km/h)**	**Roadway Type from HOTOSM roads shapefile**
Main Road "A" (Arterial)	113	None
Main Road "B" (Arterial)	113	None
Major Subdivision Road (Collector)	72	Primary
		Primary_Link
		Secondary
		Secondary_Link

Minor Subdivision Road/Local Street	56	Tertiary
		Tertiary_Link
		Living_Street
		Residential
		Service
		Unclassified (paved)

Once this classification was available, the study proceeded to calculate the MIs for each of the main materials for the paved carriageway, which were considered to be asphalt with 4 cm thickness, and a base layer of base material with 20 cm thickness. Secondary elements such as sidewalks were assumed to be of concrete. MS in weight were estimated through calculations of volumes of materials per unit of length and multiplying by their typical densities of concrete, asphalt and base material (see Table C - 14). To proceed with this, the study looked into the typical Right-of-Way Configurations from the design guidelines, in which it was found cross-sections for each of the roadway types by design (see Figure C - 1).

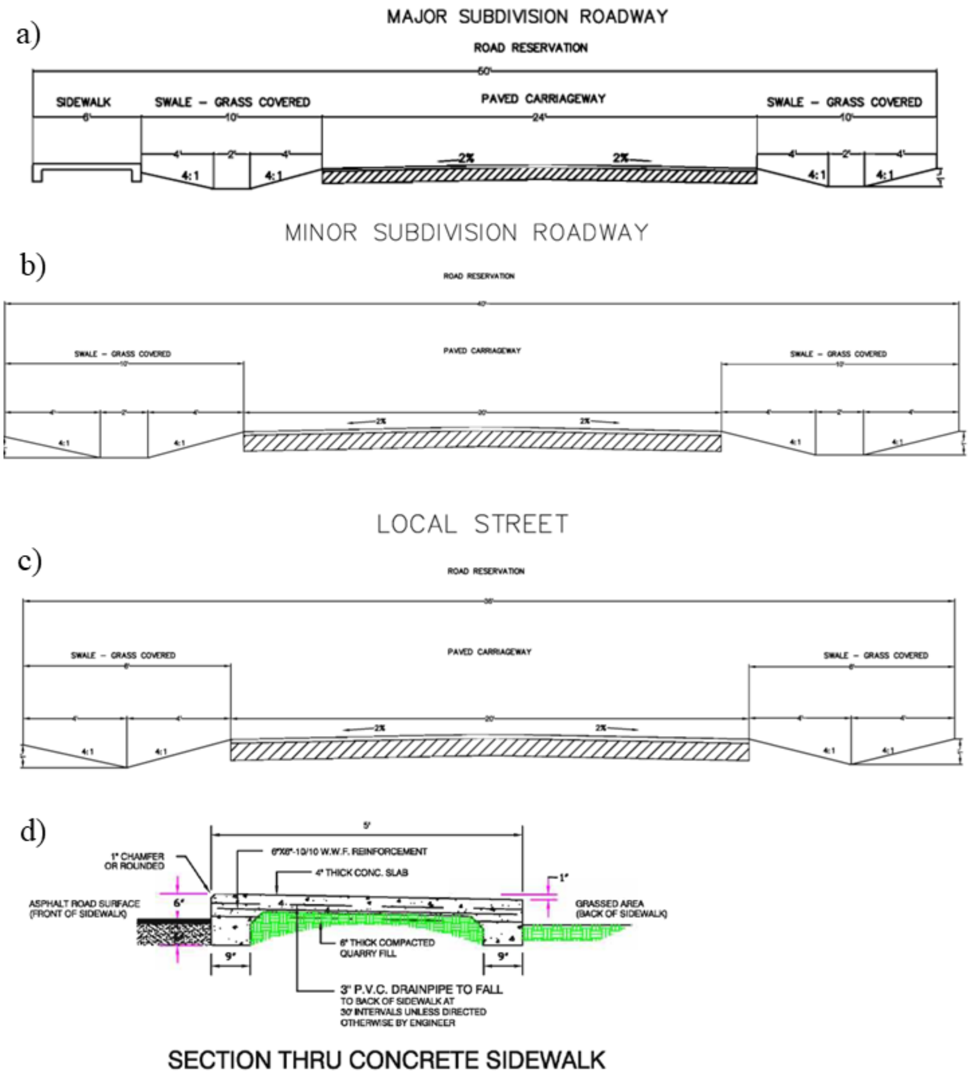


Figure C - 1 - Typical Right-of-Way configurations: cross-sections for roads in The Bahamas. 1a) corresponds to Major subdivision roadways with 24’ paved carriageway and one sidewalk. 1b) corresponds to Minor subdivision roadways with 20’ paved carriageway and no sidewalk. 1c) corresponds to Local Street roadways with 20’ paved carriageway and no sidewalk. 1d) indicates section thru concrete sidewalk. Source: Government of The Bahamas, (2004, pp. 28, 29, 42)

Based on the design guidelines, roads MI per 1 meter of length were estimated as shown in Table C - 14.

Table C - 14 - Main roads material intensities for roads

Major subdivision		**Minor Subdivision /Local Street**	
Surface road		**Surface Road**	
Asphalt thickness (cm)	4	Asphalt thickness (cm)	4
Asphalt length (cm)	732	Asphalt length (cm)	610
Total Area (m^2)	0.29	Total Area (m^2)	0.24
Total Volume per 1 ml (m^3)	0.29	Total Volume per 1 ml (m^3)	0.24
Density of Asphalt (kg/m^3)	2,300	Density of Asphalt (kg/m^3)	2,300
Total weight per 1 ml (kg)	**667**	**Total weight per 1 ml (kg)**	**552**

Base material		**Base material**	
Base thickness (cm)	20	Base thickness (cm)	20
Base length (cm)	732	Base length (cm)	610
Base Area (m^2)	1.46	Base Area (m^2)	1.22
Base Volume per 1 ml (m^3)	1.46	Base Volume per 1 ml (m^3)	1.22
Density of Base (kg/m^3)	1,680	Density of Base (kg/m^3)	1,680
Total weight per 1 ml (kg)	**2,453**	**Total weight per 1 ml (kg)**	**2,050**
Sidewalk		**Sidewalk (Not applicable)**	
Concrete Slab thickness (cm)	10		
Concrete slab length (cm)	183		
Total Area slab (m^2)	0.18		
Total slab volume per 1 ml (m^3)	0.18		
Concrete kerb thickness (cm)	15		
Concrete kerb height (cm)	23		
Total Area 2 kerbs (m^2)	0.07		
Total kerb volume per 1 ml (m^3)	0.07		
Density of Concrete (kg/m^3)	2,400		
Total weight per 1 ml (kg)	**598**		

Airport runways and seaport platforms were not clearly defined under the roads shapefile layers. To account for these, the study explored the geographic position of these facilities throughout The Bahamas (see location of Airports (OurAirports, 2022) and Seaports (SeaRates, 2022). Satellite imagery (Google Earth Pro 7.3, 2022) was utilized to visually cross-check facility locations with airport runways and seaport platforms, and a manual editing of those areas was performed for both runways and platforms where missing.

As the Building Code of The Bahamas is based generally on the South Florida (United States) Building Code (Ministry of Works & Utilities, 2003) (Government of The Bahamas, 2003), the study assumed that the Airport Pavement Design and Evaluation from the U.S. Department of Transportation (2016) were applicable for the MI of The Bahamas’s airport runways. These guidelines contain information on the design and evaluation of pavements used by aircraft at civil airports. The main materials for the pavement structure consists of a layer of asphalt with 10 cm thickness, a second layer of concrete with 12 cm thickness, and a base material layer with 25 cm thickness (see (U.S. Department of Transportation, 2016, pp. 3–17)). MS in weight were estimated through calculations of volumes of materials per unit of area and multiplying by their typical densities of Hot-Mix Asphalt, concrete, and base materials. To proceed with this, the study looked into the design guidelines where it was found a cross-section for runways (see Figure C - 2).

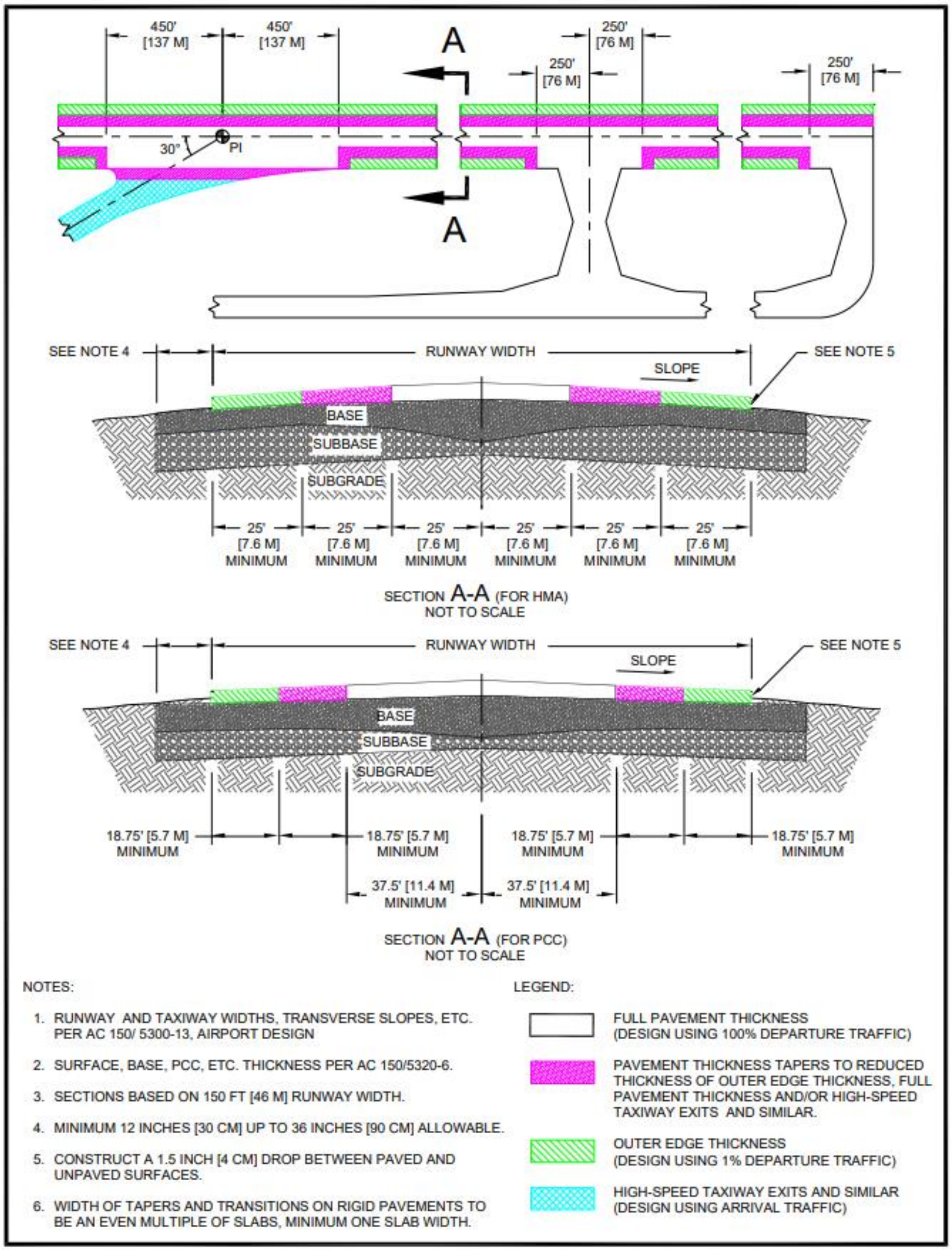


Figure C - 2 - Variable runway cross-section. Source: U.S. Department of Transportation, (2016, p. E-2)

The Building Code of The Bahamas does not contain specific design specifications for seaports cargo platforms. As these would be under similar heavy loads as the ones from airport runways, the study assumed that the Airport Pavement Design and Evaluation from the U.S. Department of Transportation (2016) could also be applicable for the seaports cargo platforms. As such, the main materials for the platforms consisted of a surface layer of 15 cm thick concrete, and 40 cm thick base material (see “Table 3-4” from the airport guidelines (U.S. Department of Transportation, 2016, p. 48). Based on these design guidelines, runways and cargo platforms MI per unit of area were estimated as shown in Table C - 15.

Table C - 15 - Estimated Airport runways and seaport platforms material intensities. Source: U.S. Department of Transportation, (2016)

Airport runways		**Seaports platforms**	
Asphalt surface		**Concrete surface**	
Asphalt thickness (cm)	10.2	Surface thickness (cm)	15.2
Total Area (m^2)	1	Total Area (m^2)	1
Total Volume (m^3)	0.1	Total Volume (m^3)	0.15
Density of Asphalt (kg/m^3)	2,400	Density of Base (kg/m^3)	2,400
Total weight per 1 m^2 (kg)	**233.7**	**Total weight per 1 m^2 (kg)**	**365.8**
Stabilized base		**Base and sub-base material**	
Base thickness (cm)	12.7	Base thickness (cm)	38.1
Total Area (m^2)	1	Total Area (m^2)	1
Total Volume (m^3)	0.13	Total Volume (m^3)	0.38
Density of Base (kg/m^3)	2,400	Density of Base (kg/m^3)	1,680
Total weight per 1 m^2 (kg)	**304.8**	**Total weight per 1 m^2 (kg)**	**640**
Sub-base			
Base thickness (cm)	25.4		
Total Area (m^2)	1		
Total Volume (m^3)	0.25		
Density of Base (kg/m^3)	1,680		
Total weight per 1 m^2 (kg)	**426.7**		

Material Stocks “*MS*” were then calculated for each transport element type “t” using the OSM classification and for each of the main material categories “m” by multiplying the transport type total gross floor area or total length “$TX_{(t)}$” by its corresponding “$MI_{(m)}$”.

Equation C - 13

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

Total material stock “MS_{total}” per main material category and for a given transport type “$TX_{(t)}$” was calculated using the following equation:

Equation C - 14

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

To calculate the total MS for each transport type, Equation C - 5 is applied for roads, airport buildings and runways, and seaport buildings and platforms.

3.- Near-future resource requirements using existing road network as a proxy

The objective of this section was to account for current levels of development and infrastructure density as well as of spatial distribution of infrastructure elements to broadly estimate future development requirements of stocks for the whole country.

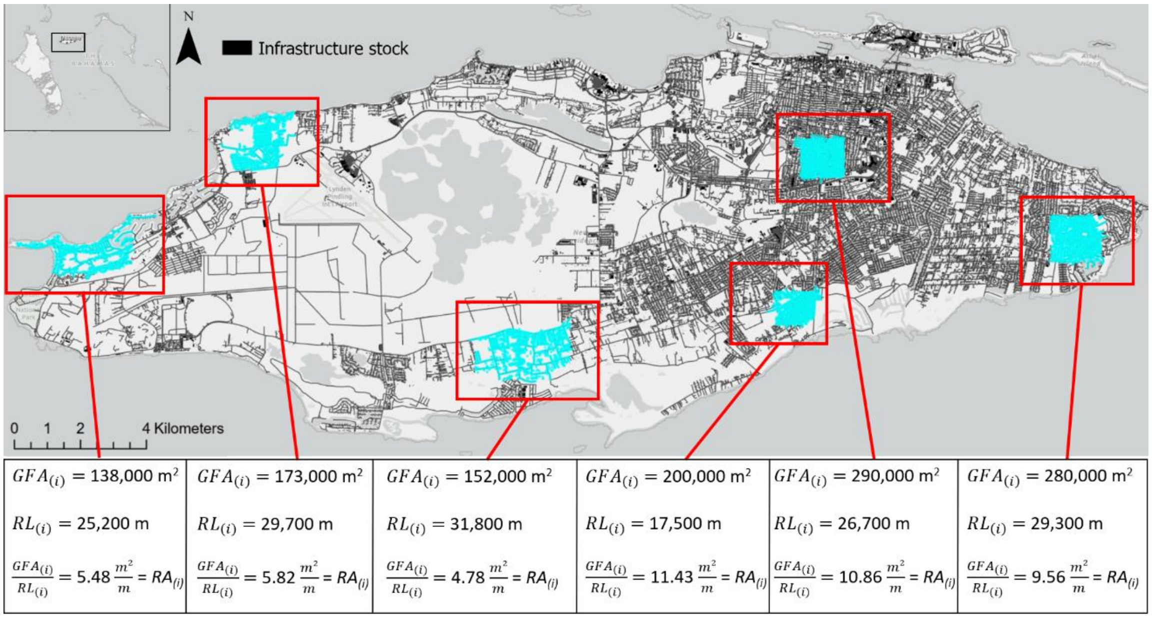
The study estimated potential future material requirements for buildings and roads in The Bahamas through two assumptions. The first corresponds to future buildings MS in which areas that currently have low building density are expected to grow in the future. Broadly, this can be approached by comparing high building dense areas vs. low building dense areas, as well as accounting for the density of roads (paved plus unpaved) in the same areas. When looking at the evolution of building stocks, the presence of roads is the first sign where development will likely happen. The second assumption corresponds to future roads MS. The study assume that currently unpaved roads will be upgraded into a paved roadway type in the future, thus changing its material intensities and subsequently their material stocks.

Future buildings - As a first step toward calculating future building MS, the study 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. As seen in Figure C - 1 (i.e., the east and west sides of New Providence), when looking at specific zones within the island, these present varying levels of development for both buildings and roads. For different locations "i", the study estimated the ratio "$RA_{(i)}$" of building gross floor area "$GFA_{(i)}$" vs. road length "$RL_{(i)}$" with the following equation:

Equation C - 15

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

A test run was conducted for the capital island of New Providence (see Figure C - 1). This initial test showed us that, for this island, $RA_{(i)}$ ranges from 9.6 to 11.4 for highly dense areas, and from 4.8 to 5.8 for less dense areas.



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

Figure C - 3 - (Data from Figure 9 in Chapter 5) - Ratios RA(i) of building gross floor area GFA(i) per road length RL(i) for different highlighted zones in New Providence in 2021

As each district has its own infrastructure, with its own building footprint GFA and roads length, one can see that there are different levels of infrastructure development. To account for country-wide variations, the study estimated total GFA and total RL for each district division by creating a homogeneous country-wide grid of 500m X 500m (see Figure C - 4) and summarizing total GFA and total RL per each grid cell (see Figure C - 5). The study assumed that the potential maximum building development will be reached the higher RA is. Thus, areas with a lower ratio will have the potential to reach a higher ratio in the future, requiring more materials for that development. As a proxy to predict future material requirements for building stocks, the study utilized Equation C - 7.

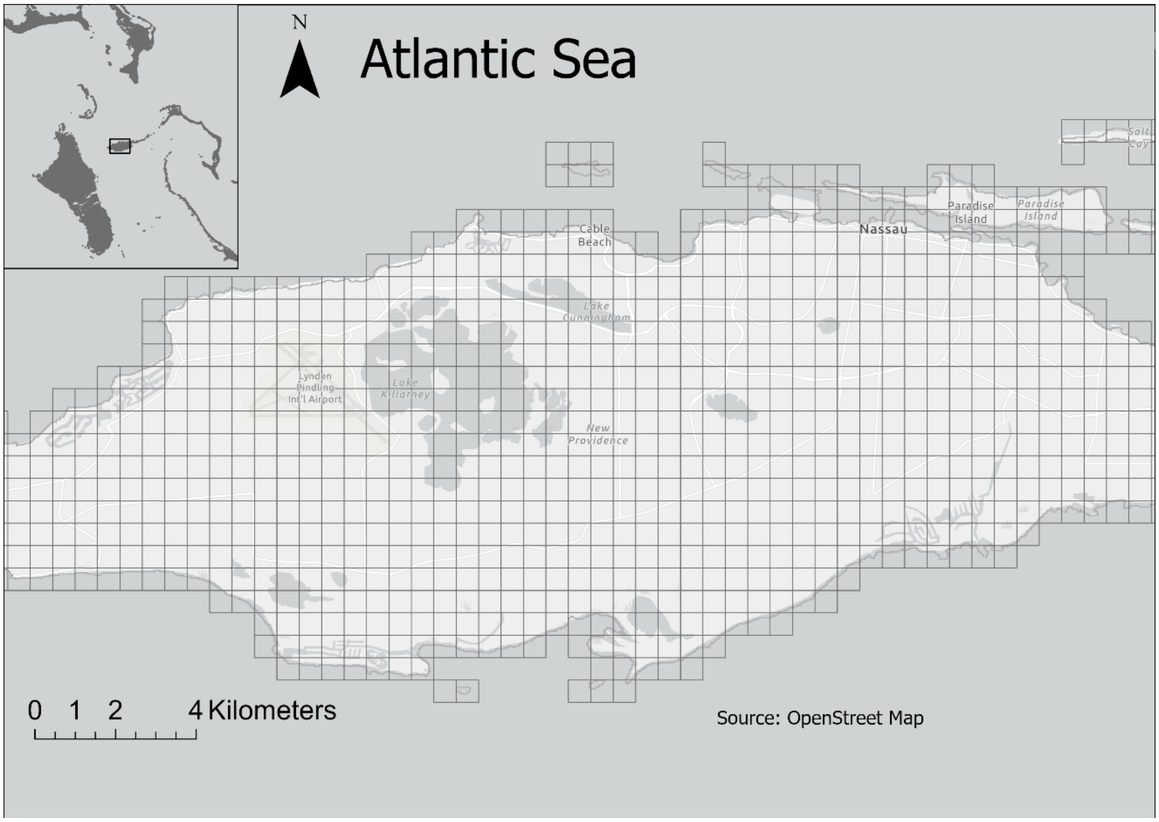
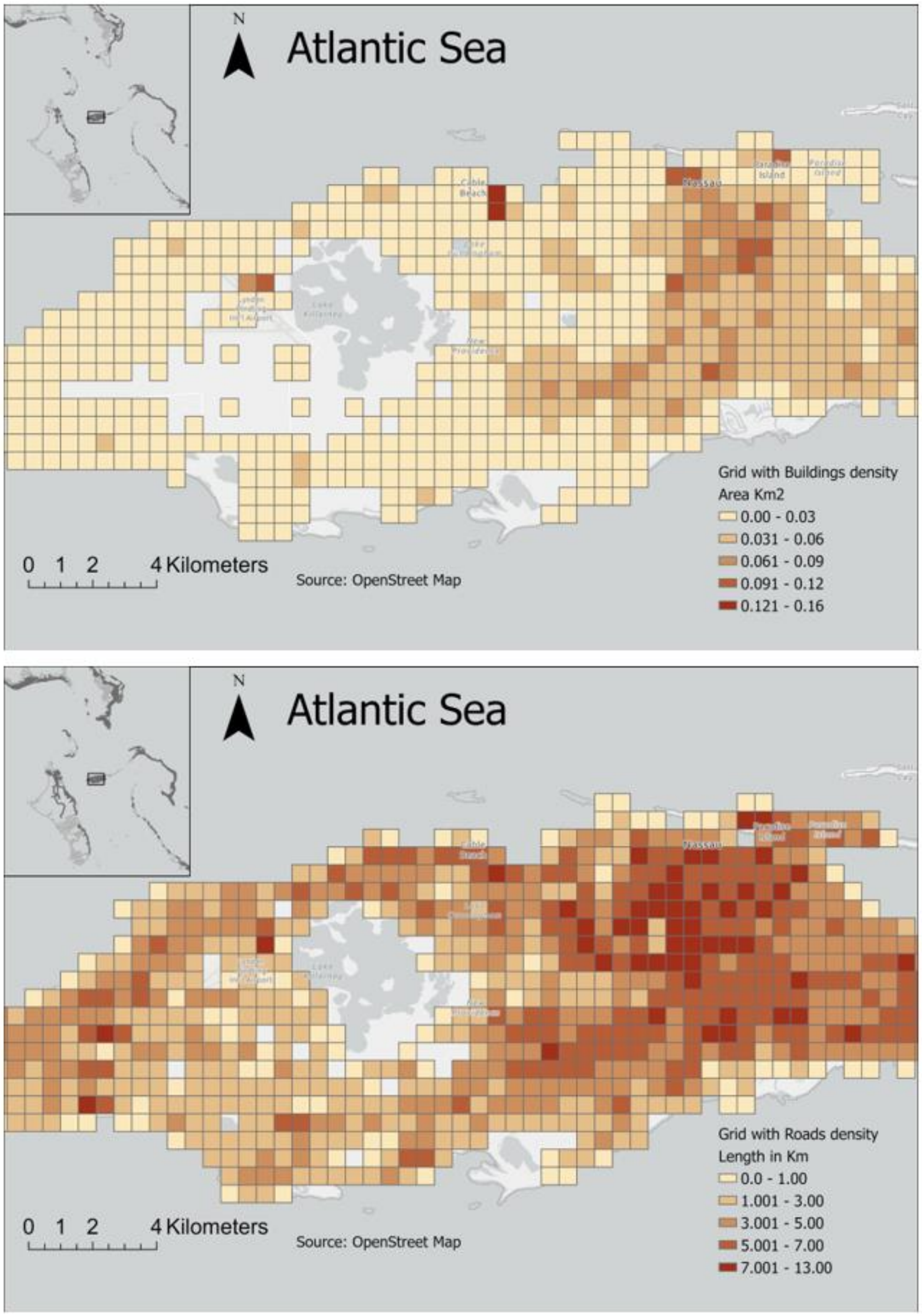


Figure C - 4 - Grid 500m X 500m that covers all The Bahamas. Image shows zoomed-in section of New Providence.



Source: OpenStreet Map

Source: OpenStreet Map

Figure C - 5 - Buildings and Roads Density Grid in The Bahamas. Image shows zoomed-in section of New Providence

Total future building materials “FM” was then 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.

Equation C - 7

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

The average MI was based on the overall MIs for each building use-type and the current shares of building MS use-types (see Table C - 16).

Table C - 16 - Average MIs based on shares of buildings and current MS distribution in The Bahamas. Source: own estimations from Humanitarian OpenStreetMap Team, (2021a) and Government of The Bahamas, (2016)

Building category	Structure type	Shares of buildings (%)	Structure MI (kg/m^2)	Current MS distribution from our results (%)	Average MI (kg/m^2)
Residential	Concrete	85	1880	67	1152.4
	Timber	10	516		
	Concrete/timber	5	1409		
	Total average	**100**	**1720.5**		
Commercial	Concrete	1880	1880	27	507.6
Industrial	Steel	100	2129	3	63.87
Governmental	Concrete	100	1880	2	37.6
Other	Timber	100	516	2	10.32
Average MI					**1771.8**

Future Roads **-** The objective of this section of the methodology aimed at describing the procedure in which the study calculated future material requirements for roads for the whole country. The estimation of future road stocks for development was more straightforward.

Our assumption was that current unpaved roads will become paved in the future. From the OSM roads shapefile layers, these potentially include the ones with the tags of “path”, and the “unclassified” roads that will eventually fall under the main roadtype of Minor Subdivision Road/Local Street. The study accommodated these under the road type of “minor subdivision road/local street”. In addition, through an analysis of the roads network shapefile and direct visual observation of satellite imagery, the study manually filtered and considered those areas containing “track” roads that display a distinct spatial arrangement characteristic of the preliminary works for future urban development (see Figure C - 6). Once the roadways that would become paved in the future were selected and applied their respective material intensities, the study proceeded to calculate the future material requirements for each of the main components of the roads.

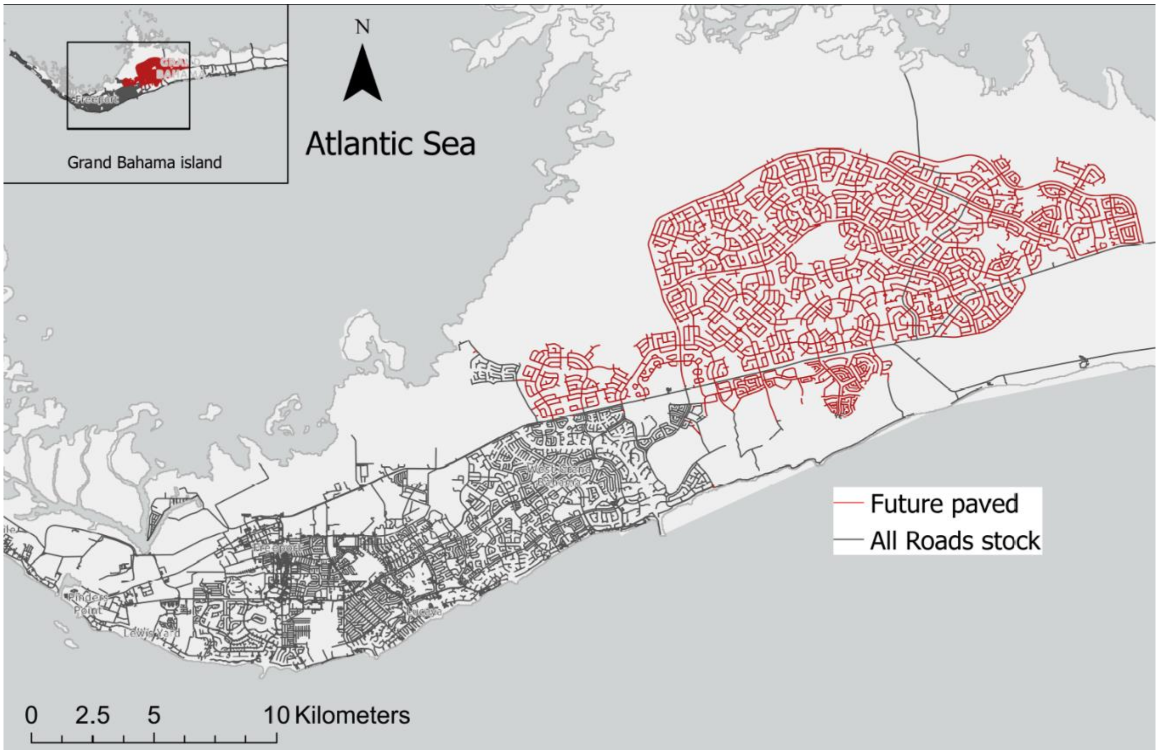


Figure C - 6 - Marked in red color are the "track" roads that were to be considered as "paved" in the future as these areas display a distinct spatial arrangement characteristic of the preliminary works for future urban development. Image shows zoomed-in section of Grand Bahama island.

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

Equation C - 16

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

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

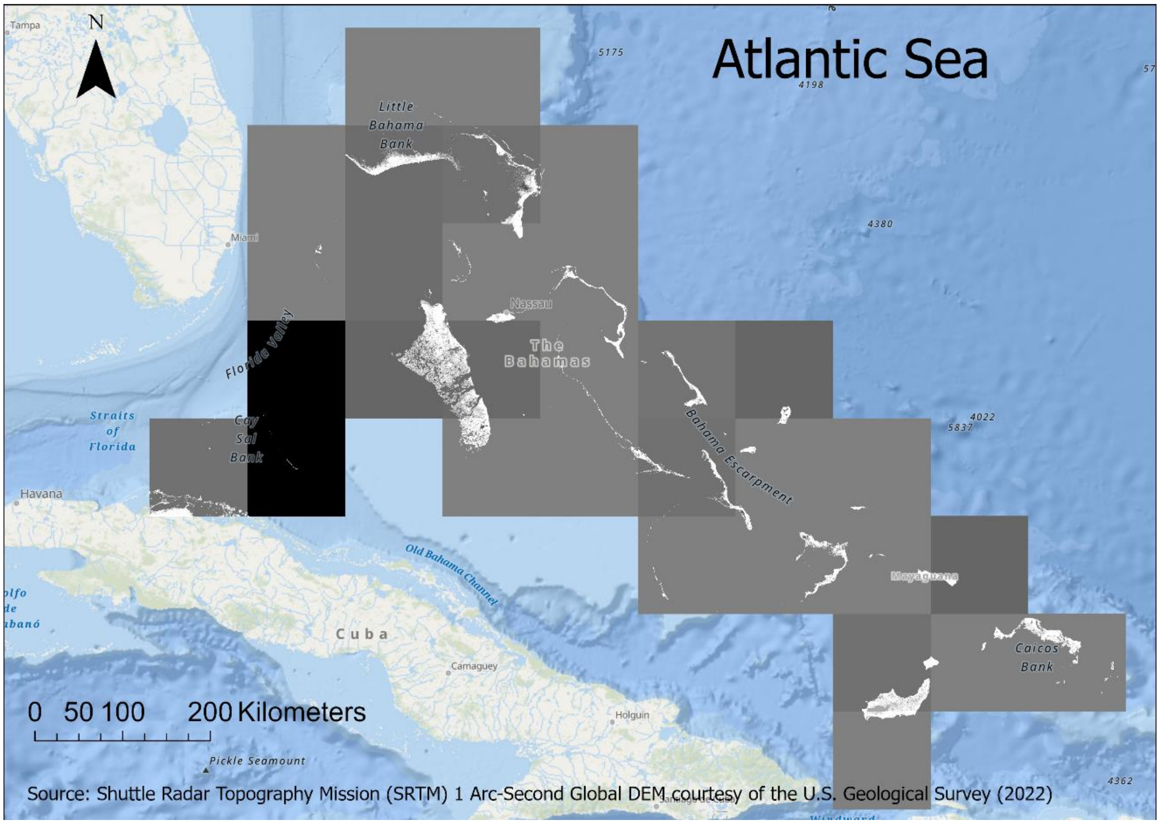
Equation C - 17

$$FMS_{total} = \sum FMS_{(r,m)} = MS\ Concrete_{(r,m)} + MS\ Asphalt_{(r,m)} + MS\ Base\ Material_{(r,m)}$$

4.- Sea-level rise scenarios

Our goal in this section was to showcase the potential effects of sea level rise (SLR) on infrastructure stock for the whole country through the simulation of different SLR scenarios. These were based on assessments of 1 meter (Intermediate-High projection) and 2 meter (Highest projection) estimates of global SLR by

2100 using mean sea level in 1992 as presented by the National Oceanic and Atmospheric Administration (Parris et al., 2012). A third simulation of 3 meters presents a more critical situation where SLR continues to rise past the year 2100. For data on elevations, the study used a set of 1 Arc-Second Global digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) from the U.S. Geological Survey (USGS, 2022). The first step was to download all the raster data based on the geographical coordinates of the extent of The Bahamas (see Figure C - 7). This resulted in a mosaic of 31 raster that were merged as a single raster. Then, polygon shapefile layers from the filtering of elevations from the DEM (for 1, 2, and 3 meters) were created. The impacts of SLR were then estimated by overlaying the SLR polygons on buildings and roads stock data and summarizing the buildings and roads stock that would be exposed under the scenarios (see Figure 8 and Table 14 from Chapter 5).



Source: Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM courtesy of the U.S. Geological Survey (2022)

Figure C - 7 - Individual raster files with elevation data for The Bahamas before merge. Source: Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM courtesy of the U.S. Geological survey (USGS, 2022)

For the qualitative impacts, historical satellite imagery (see Figure C - 8, Figure C - 9, Figure C - 10), as well as land-use plans were consulted. Different patterns of development in the country were highlighted through direct visual observation of historical satellite imagery and revision of proposed land-use plans.

Together with the generated SLR polygons and current spatial distribution of buildings and roads stocks, the study was able to showcase some of the potential effects of SLR on current stock and future development**.**

Figure C - 8 - Evolution of infrastructure in The Bahamas. Image shows zoomed-in section of New Providence. Source: Google Earth Pro®, (2021)

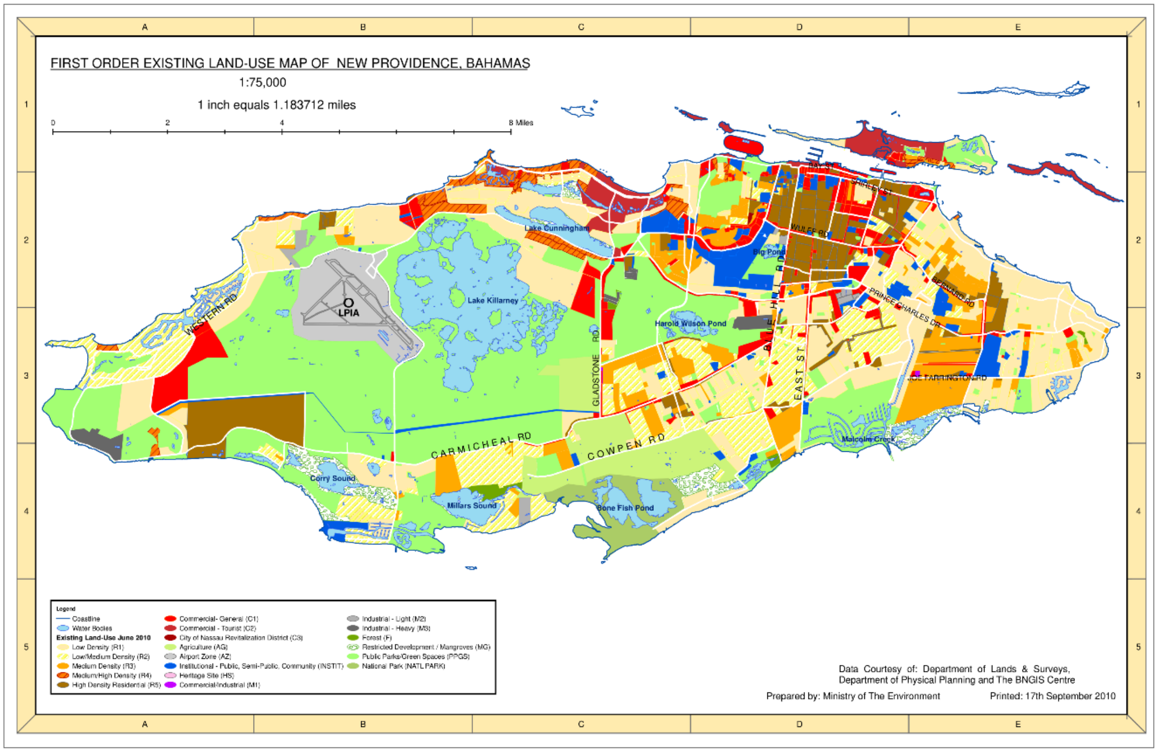


Figure C - 9 - First Order Existing Land-use Map of New Providence, Bahamas. Source: Government of The Bahamas, (2010)

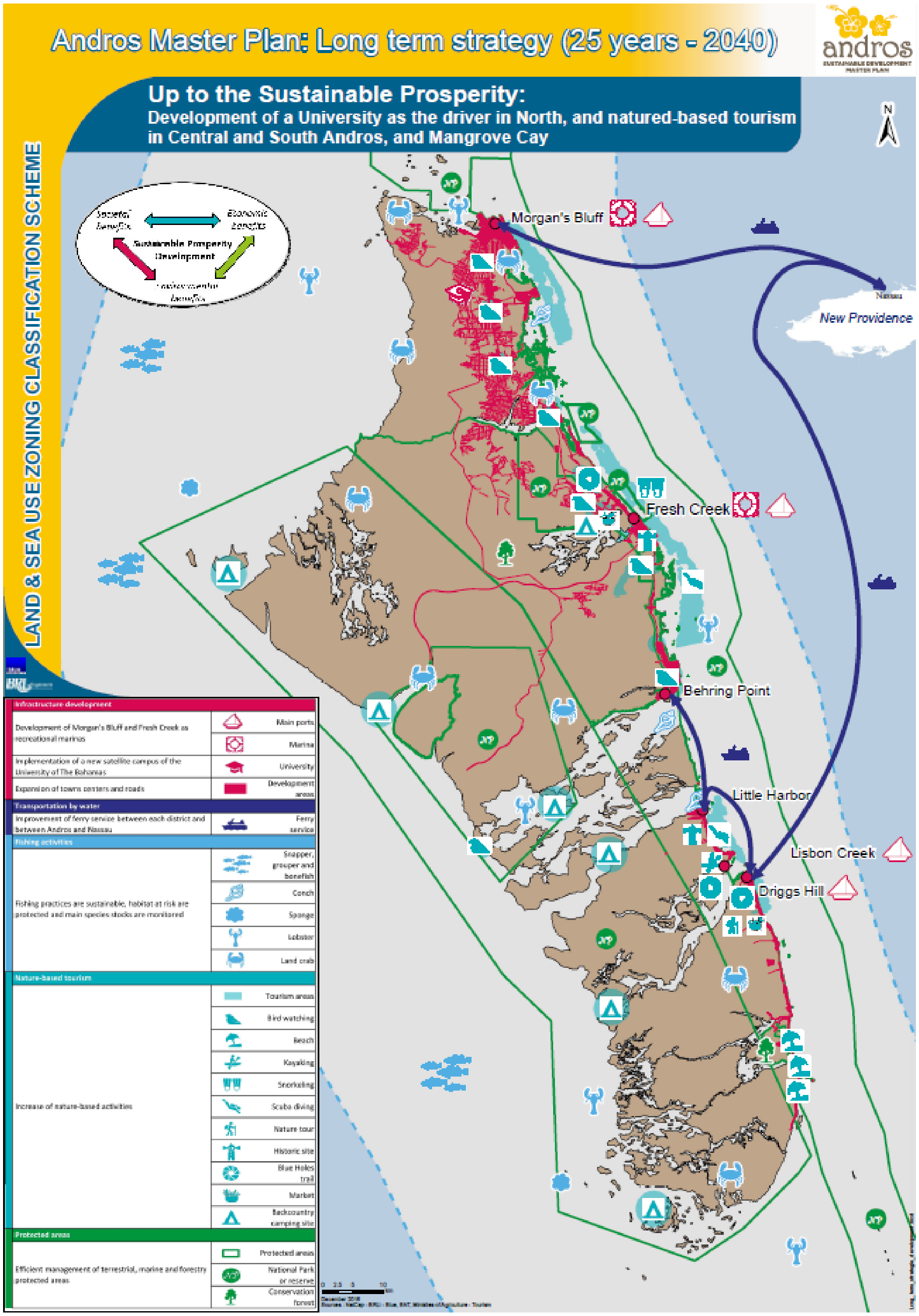


Figure C - 10 - Andros Master Plan: Long term strategy (25-years – 2040). Source: Government of The Bahamas, (2017)

5.- Future Neighborhood development zones

The purpose of this section is to try to roughly identify potential future neighbor development zones across The Bahamas. The identification of these zones may serve as input for planners and decision makers to improve the management of new development. The study used the November 2021 OpenStreetMap (OSM) GIS building footprint shapefile (Humanitarian OpenStreetMap Team, 2021a) and the November 2021 OSM road network shapefiles extracted through the Humanitarian Data Exchange project (HOTOSM), and Geofabrik GmbH (Geofabrik GmbH, 2021; Humanitarian OpenStreetMap Team, 2021b). The study worked with both files under the ArcGIS Pro 2.8.3 software

By visually comparing current satellite imagery from Google Earth (Google Earth Pro®, 2021) with the OSM road network dataset, it was revealed that several distinct dense unpaved street networks had few buildings in the surrounding areas. When looking at the evolution of building stocks, the presence of a dense street network, especially with a distinct conventional cul-de-sac pattern is an early sign that indicates where development will likely happen. In order to systematically identify such areas, as a first step the study created a new field within our previously created 500m X 500m grid where it was calculated the ratio of road length (km) vs building gross floor area (GFA) (km^2).

Step 2 was to display the densities based on the values of the ratios. 4 classes were identified as seen in Table C - 17. Next the the areas larger than 1,000 km/km^2 were selected. This preliminary filter gave an estimation of future neighbourhood areas, however further refining was needed as there was a need to remove the intercity roads cells (see Figure C - 11).

Table C - 17 - Density values for the ratios of road length vs GFA in The Bahamas

Classes	Density value (km/km2)
Class 1	1 ≤ 1,000
Class 2	1,000 ≤ 10,000
Class 3	10,000 ≤ 100,000
Class 4	> 100,000

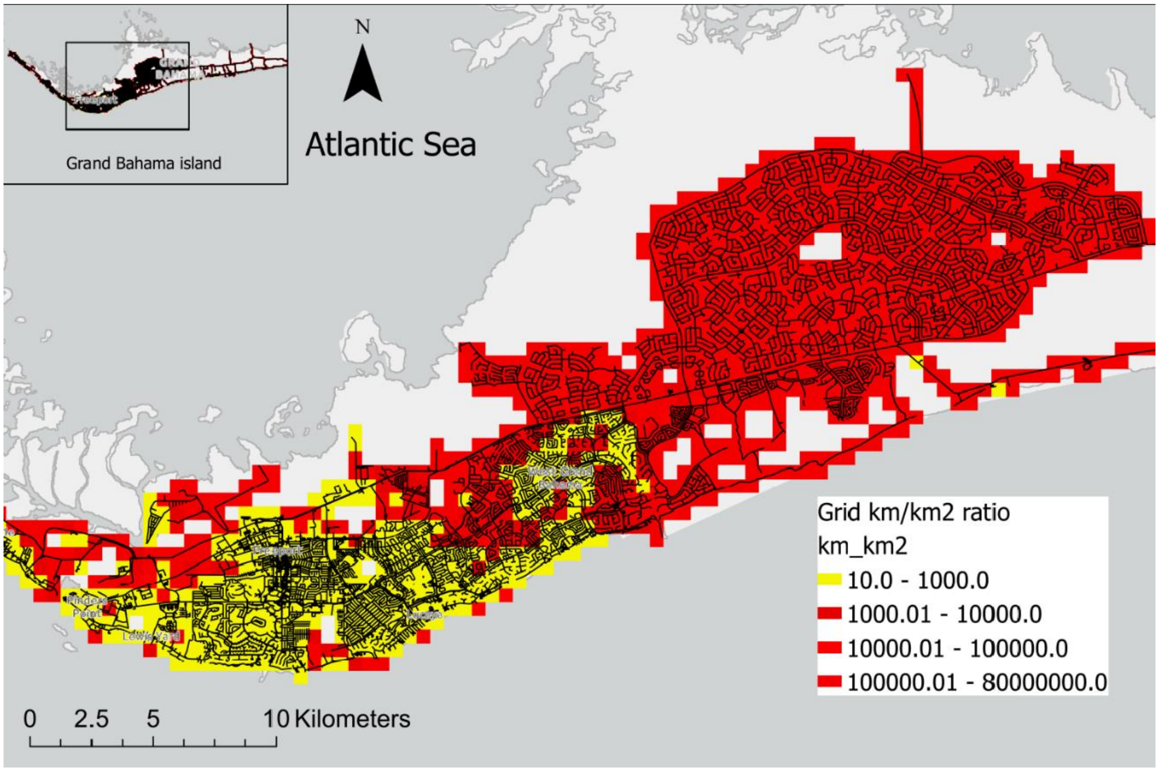


Figure C - 11 - Roads length VS Building GFA. In red are the cells with values greater than 1,000 km/km2, which broadly correspond to future neighborhood areas. Image shows zoomed-in section of Grand Bahama island

For Step 3, the study created a "polygon neighbor" table with statistics based on spatial polygon contiguity (coincident edges, or nodes) between source polygons and neighbor polygons utilizing that previous grid as a base. The resulting table was then exported to Excel and a pivot table was created summarizing the borders and corners for each unique grid cell. This table was then joined to the grid with areas larger than 1,000 km/km^2. A filter of the grid cells with a value of borders equal or less than 2 was performed, which resulted in highlighting most of the inter-city roads (see Figure C - 12).

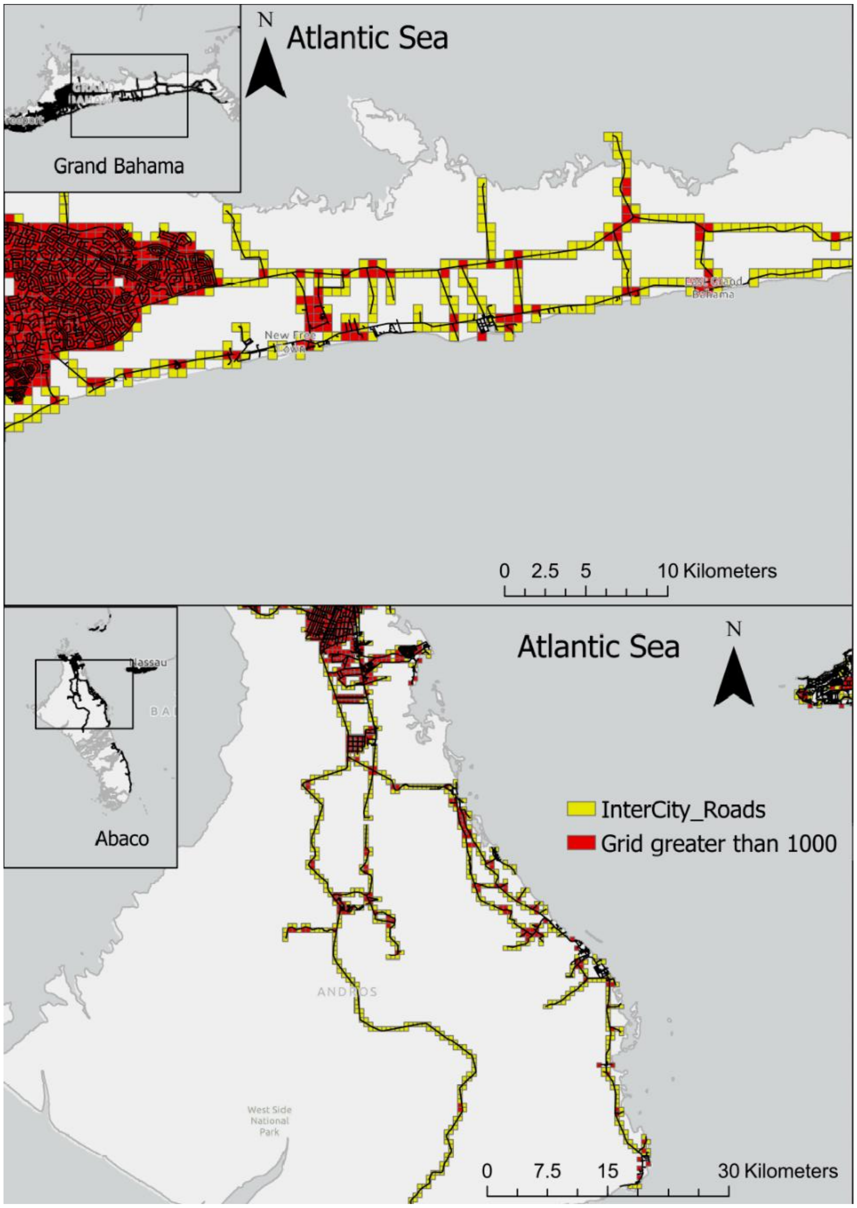


Figure C - 12 - Identification of InterCity Roads (yellow), and future neighborhood areas (red). Image shows zoomed-in section of Grand Bahama island and Abaco island

The study managed to automate this process up to this point, however, the last filtering had to be performed manually. Step 4 involved a subjective human intervention to perform a selection of grid cells showing the presence of forest/agriculture areas, especially within the islands of Abaco and Andros, which brings a certain degree of uncertainty in the identification of these future neighborhood areas. Once done, these grid cells, together with the intercity roads were removed from the original “grid greater than 1,000 km/km^2”, generating the future neighborhood areas. These simulations on potential future neighborhood areas bring about certain locations across Grand Bahama island, North Andros, west Inagua, and Mayaguana as seen in Figure C - 13. The utilization of OSM data can also serve as a “predictive tool” to strategically map future development areas across the country for future land-use zoning and (risk) planning purposes.

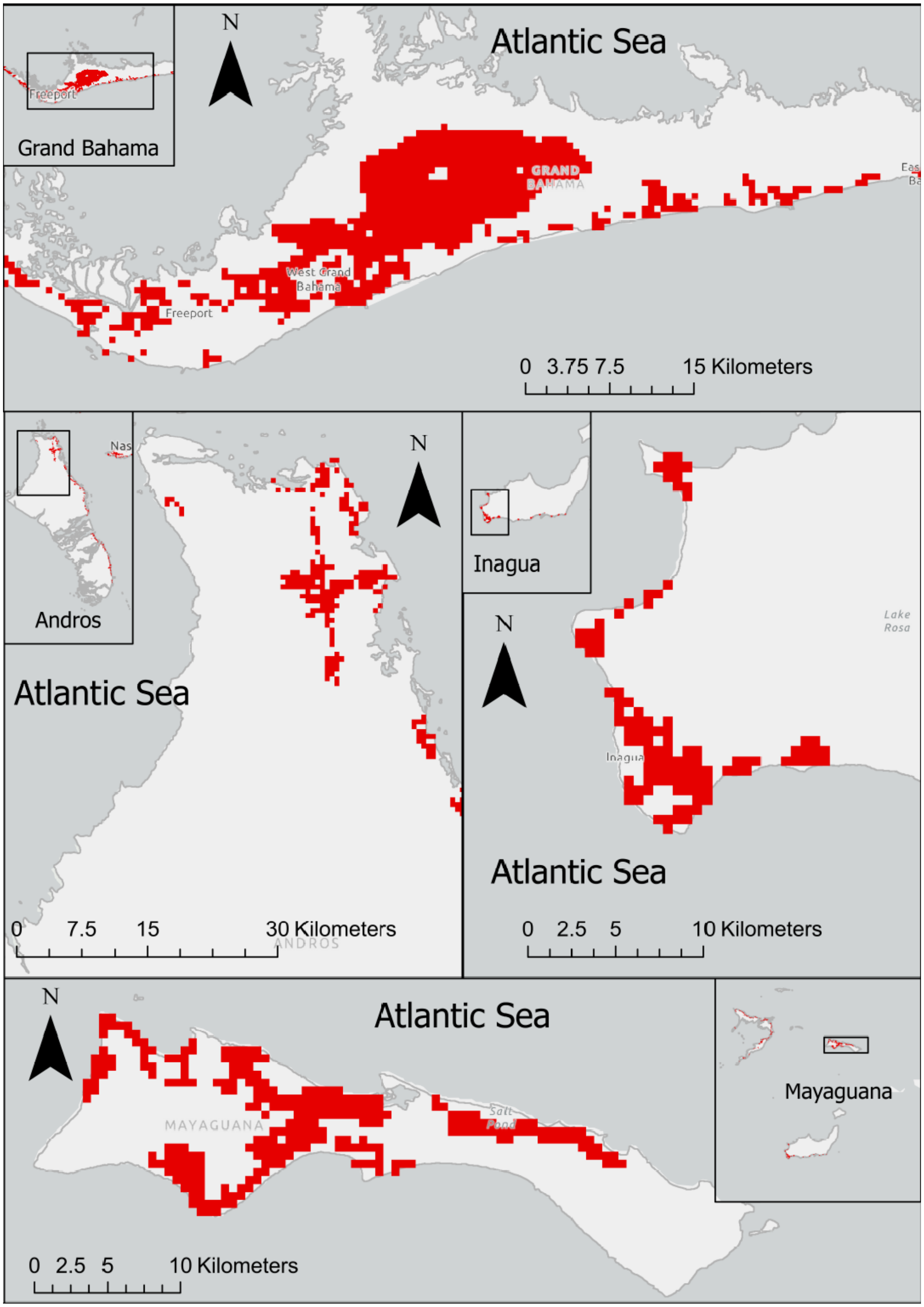


Figure C - 13 - Simulations on future neighborhood development areas (in red) across The Bahamas. Image shows zoomed-in section of Grand Bahama, Abaco, Inagua, and Mayaguana islands

Table C - 18 - Key seaports and airports data, by numbers and by per capita, for some SIDS around the world. Source: The World Bank, 2022; OpenStreetMap, 2021; Worldometer, 2022; World Port Source, 2022; Searates, 2022; OurAirports, 2022

Caribbean	Population 2020	Land area km2	# of islands	Inhabited islands	# seaports	# airports	GDP per capita (2020, US$)	seaports per 10,000 inhabitants	airports per 10,000 inhabitants
The Bahamas	393,244	14,000	700	17	8	67	25,194	0.203	1.704
Anguilla	15,003	90	21	1	1	2	20,438	0.667	1.333
Antigua & Barbuda	97,929	440	10	2	1	3	13,993	0.102	0.306
Aruba	106,766	180	1	1	3	3	30,253	0.281	0.281
Barbados	287,375	430	2	1	1	2	15,374	0.035	0.07
British Virgin Islands	30,231	150	54	16	3	5	49,357	0.992	1.654
Cuba	11,326,616	106,440	1600	2	37	143	9,478	0.033	0.126
Dominica	71,986	750	3	1	3	2	7,004	0.417	0.278
Dominican Republic	10,847,910	48,320	70	1	14	42	7,268	0.013	0.039
Grenada	112,523	340	20	3	1	3	9,262	0.089	0.267
Haiti	11,402,528	27,560	59	1	11	21	1,272	0.01	0.018
Jamaica	2,961,167	10,830	49	1	15	27	4,665	0.051	0.091
Montserrat	4,992	100	1	N.D.	2	2	13,523	4.006	4.006
Puerto Rico	2,860,853	8,870	143	5	22	67	32,291	0.077	0.234
St. Kitts and Nevis	53,199	260	2	2	2	2	18,438	0.376	0.376
St. Lucia	183,627	610	1	1	4	2	8,805	0.218	0.109
St. Vincent and the Grenadines	110,940	390	32	5	5	6	7,278	0.451	0.541
Trinidad & Tobago	1,399,488	5,130	23	2	11	3	15,426	0.079	0.021
U.S. Virgin Islands	104,425	350	53	3	6	9	38,137	0.575	0.862
Pacific									
American Samoa	55,191	200	5	5	1	4	12,845	0.181	0.725
Cook Islands	17,564	240	15	N.D.	1	10	21,884	0.569	5.693
Federated States of Micronesia	548,914	700	607	4	2	6	3,565	0.036	0.109
Fiji	896,445	18,270	840	2	5	35	5,058	0.056	0.39
French Polynesia	280,908	3,660	118	67	7	57	14,324	0.249	2.029
Guam	168,775	540	1	N.D.	1	4	34,624	0.059	0.237
Kiribati	119,449	810	33	20	3	23	1,654	0.251	1.926
Marshall Islands	59,190	180	34	5	2	35	4,130	0.338	5.913
Nauru	10,824	20	1	N.D.	1	1	10,580	0.924	0.924
New Caledonia	285,498	18,280	6	6	7	27	34,789	0.245	0.946
Niue	1,626	260	1	N.D.	1	1	16,551	6.15	6.15
Northern Mariana Islands	57,559	460	14	3	3	12	20,660	0.521	2.085
Palau	18,094	460	340	10	2	3	14,244	1.105	1.658
Papua New Guinea	8,947,024	452,860	600	1	19	601	2,757	0.021	0.672
Samoa	198,414	2,830	9	4	1	5	4,068	0.05	0.252
Solomon Islands	686,884	27,990	992	N.D.	14	38	2,251	0.204	0.553

Timor-Leste	1,318,445	14,870	3	N.D.	1	13	1,443	0.008	0.099
Tonga	105,695	720	170	N.D.	3	6	4,625	0.284	0.568
Tuvalu	11,792	30	9	N.D.	1	3	4,143	0.848	2.544
Vanuatu	307,145	12,190	83	N.D.	2	36	2,870	0.065	1.172
Africa, Indian Ocean, Mediterranean and South China Sea (AIMS)									
Bahrain	1,701,575	760	33	14	3	11	20,410	0.018	0.065
Cape Verde	555,987	4,030	10	N.D.	7	10	3,064	0.126	0.18
Comoros	869,601	1,861	4	N.D.	3	4	1,421	0.034	0.046
Guinea-Bissau	1,968,001	28,120	29	18	4	7	728	0.02	0.036
Maldives	540,544	300	1,192	187	1	28	6,924	0.018	0.518
Mauritius	1,271,768	2,030	79	1	1	4	8,628	0.008	0.031
Sao Tomé and Príncipe	219,159	960	2	N.D.	2	4	2,158	0.091	0.183
Seychelles	98,347	460	115	N.D.	1	22	10,764	0.102	2.237
Singapore	5,850,342	700	64	N.D.	2	11	59,798	0.003	0.019

6.- OpenStreeMap files manipulation.

For the purpose of Chapter's 5 study, it was necessary to work with the most recent and available shapefiles containing data on building footprints and road network in The Bahamas. As of the time of writing of the manuscript, the November 2021 file extracts were available and were downloaded from the HOTOSM (https://data.humdata.org/dataset/) and Geofabrik GmbH (https://download.geofabrik.de/) platforms. However, these platforms work with data extracts from the OpenStreetMap (OSM) project. The OSM project is constantly updated, usually on a monthly basis.

In case someone would like to visit the HOTOSM and Geofabrik GmbH platforms to download and work with the November 2021 OSM extracts utilized in the study, one would be faced with an updated version of the same file (May 2022 version as of the time of writing of this paper), and with no option to select a timeframe from where to download a specific point in time. Once the newest version comes up, the old extract version is uploaded and stored in a single whole-planet file containing all nodes, ways and relations that make up the planet.

These files go from the year 2012 up to today. Since these files contain information for the whole planet, they are very large in size (+20 gb compressed files for the year 2012 up to +100gb for the 2022 files). Moreover, these come in a "*.OSM" extension file specific to OpenStreetMap, which will require extra processing to work under other GIS platforms such as ArcGIS Pro. This full planet history file may be useful if you want to consult specific times and zones, or to perform "Historical Coverage" and more statistical analyses (visit https://wiki.openstreetmap.org/wiki/Planet.osm/full for more explanation on these type of files).

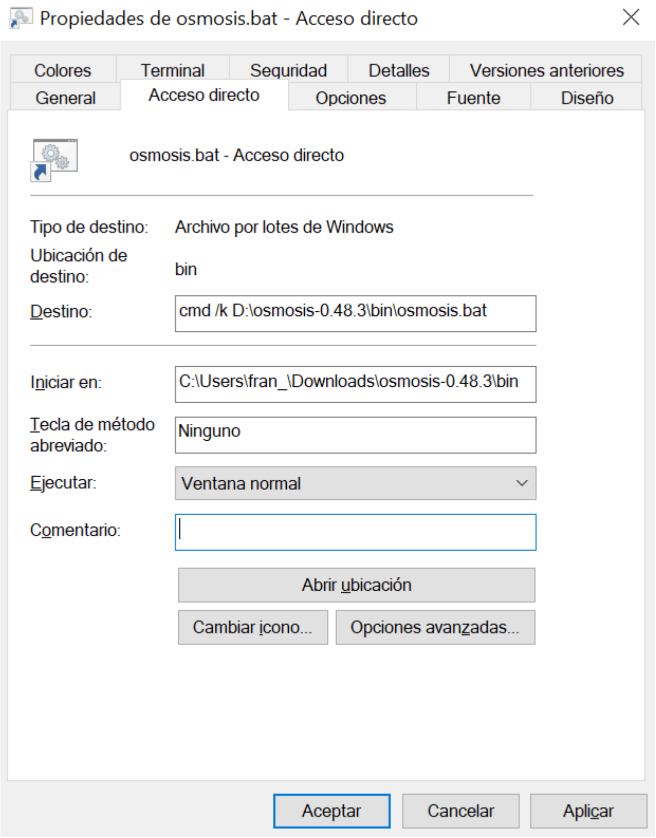
As a way to aid in the process of spatial analysis of historical data for a specific zone, an explanatory step-by-step example of how to download and work with files downloaded from OpenStreetMap was created. These simulations were run under 64 bits Windows 10 Home version 21H2, Intel® Core™ i5-8265U CPU @ 1.60GHz 1.80 GHz, 8.00 GB RAM.

Step 1 - Our work location was first prepared on an external 5 tb hard drive “D:\” anticipating the size of the downloaded and uncompressed files. One way to work with *.osm* files is through a command line Java application for processing OSM data called “*Osmosis*” (see https://wiki.openstreetmap.org/wiki/Osmosis for more details). The tool can be downloaded from https://github.com/openstreetmap/osmosis/releases/tag/0.48.3. The tool downloaded was Osmosis (osmosis-0.48.3.zip) and it was decompressed its contents in the working location (D:\osmosis-0.48.3).

Step 2 – Next, the download of the historical data was performed from the following link: https://planet.openstreetmap.org/planet/2013/. In this example, the January 2013 “planet-130102.osm.bz2” file with 25 gb size was downloaded.

Step 3 - Once downloaded, the file was decompressed, which resulted in a .osm file with close to 400 gb size, and placed it in the “bin” folder (D:\osmosis-0.48.3\bin\planet-130102.osm).

Step 4 - The “osmosis.bat” file was located under the “bin” folder (D:\osmosis-0.48.3\bin\Osmosis.bat) and a shortcut (“Acceso directo” in Spanish) to the file was created by first opening its Properties, and on the Shortcut tab inserting “cmd /k” at the beginning of the “Target” (“Destino” in spanish) as indicated in Figure C - 14 below. Inserting those lines (“cmd/k”) enables the file to be run in a window that stays open when double-clicking the “osmosis.bat” file.



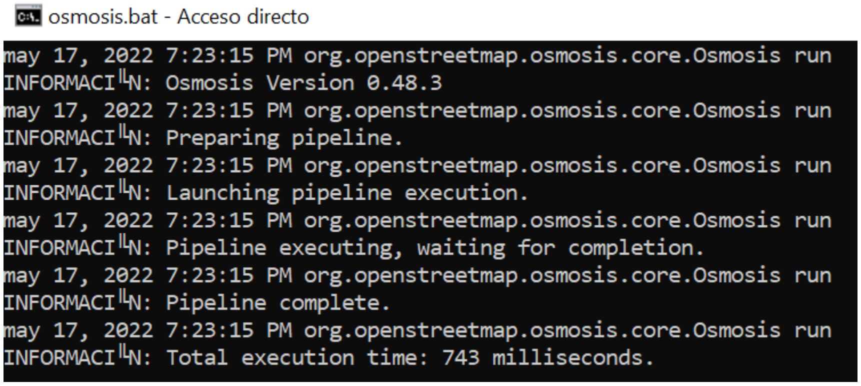
Propiedades de osmosis.bat - Acceso directo

osmosis.bat - Acceso directo

Tipo de destino: Archivo por lotes de Windows
Ubicación de destino: bin
Destino: cmd /k D:\osmosis-0.48.3\bin\osmosis.bat
Iniciar en: C:\Users\fran_\Downloads\osmosis-0.48.3\bin
Tecla de método abreviado: Ninguno
Ejecutar: Ventana normal
Comentario:

Figure C - 14 - Creation of a shortcut to the "osmosis.bat" file. Note that "cmd/k" was added at the beginning of the "Target"

Step 5 – When double clicking on the newly created "osmosis.bat" file, the window that opens should look something like in Figure C - 15 below.



osmosis.bat - Acceso directo

```
may 17, 2022 7:23:15 PM org.openstreetmap.osmosis.core.Osmosis run
INFORMACI╙N: Osmosis Version 0.48.3
may 17, 2022 7:23:15 PM org.openstreetmap.osmosis.core.Osmosis run
INFORMACI╙N: Preparing pipeline.
may 17, 2022 7:23:15 PM org.openstreetmap.osmosis.core.Osmosis run
INFORMACI╙N: Launching pipeline execution.
may 17, 2022 7:23:15 PM org.openstreetmap.osmosis.core.Osmosis run
INFORMACI╙N: Pipeline executing, waiting for completion.
may 17, 2022 7:23:15 PM org.openstreetmap.osmosis.core.Osmosis run
INFORMACI╙N: Pipeline complete.
may 17, 2022 7:23:15 PM org.openstreetmap.osmosis.core.Osmosis run
INFORMACI╙N: Total execution time: 743 milliseconds.
```

Figure C - 15 - Appearance of the command prompt window of osmosis.bat

Step 6 – The following command was run in the osmosis-bat command prompt window. For your own work, you can copy-paste this command as follows:

```
bzcat "planet-130102.osm" | osmosis --read-xml file="planet-130102.osm" enableDateParsing="no" --bounding-box left="-80.706" right="-72.411" top="27.479" bottom="20.705" --write-xml file="Name_of_file_output.osm"
```

Note: technically, a *“*.osm”* file could be opened with several GIS applications, however the full decompressed planet history file size may be too heavy to be loaded (+400 gb for the January 2013 file). The previous command allows you to extract an area of your choice from the whole planet. The simplest way to do that is by selecting a rectangle or “bounding box” corresponding to your study area. In this example, our “bounding box” corresponds roughly to the coordinates extent of The Bahamas marked in yellow: Top-left corner coordinates: 27.479 N, 80.706 W; Bottom-right corner: 20.705 N, 72.411 W. If you would require other region/city just change the coordinates.

The newly created file through the utilization of the Osmosis tool will be smaller in size and this can now be more easily opened with some GIS applications. For the purposes of Chapter 5, the software Quantum GIS “QGIS” Desktop 3.16.11 was selected to open that newly extracted file.

Step 7 - From the QGIS browser, our newly created file can be viewed, containing the indicated bounding box. You will find Lines, Multilinestrings, Multipolygons, Other_relations, and Points, as seen in Figure C - 16.

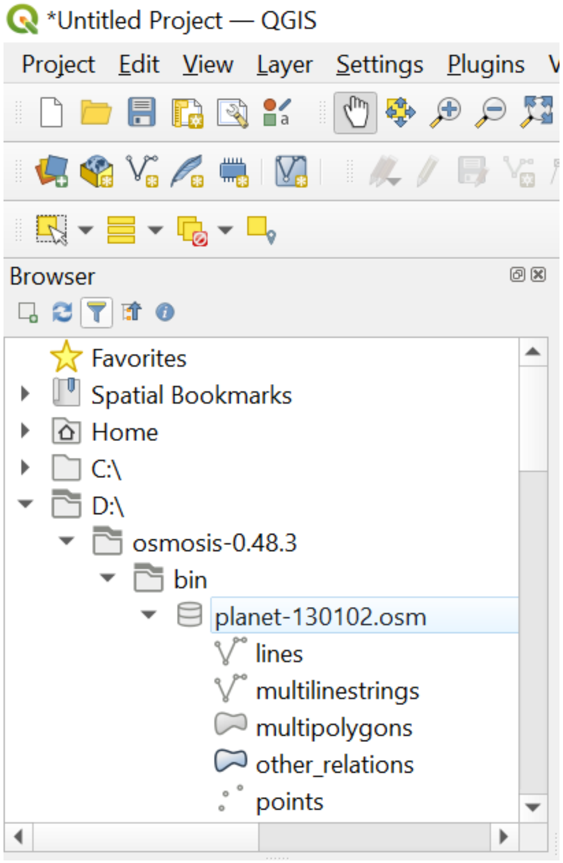


Figure C - 16 - Browsing the contents of our bounding box extract from our January 2013 planet history file

Step 8 – You can either work directly under QGIS or you can also export the layer to an ESRI Shapefile to work under ARcGIS by right clicking the layer – Export Layer – To file.

Note: As all the information of OpenStreetMap is contained in these few layers, when displayed, there will be a need to perform a "cleaning" before actually making sense of the contents of the files. It is suggested that a first exploration of data through the Table of Attributes should be performed.

Overall, one of the obstacles found with regards to the planet files is clearly their sizes. Depending on your broadband speed and computer specifications, it could even take a couple of days, from downloading the files, to having the final bounding box file. Moreover, our method involves decompressing the whole planet history file, and then loading it in Osmosis to extract the bounding box, which then is loaded into a GIS application to finally filter the information required. With our computer specifications, just decompressing a 25 gb that turned into a +400 gb file would take a couple of days and loading the resulting file into Osmosis and running the script to extract the bounding box would take a day or two. There are other tutorials online where they claim that you can directly extract your bounding box “on the fly” by utilizing Osmosis without the need of decompressing the full planet file, however based on the experience gained through Chapter 5 and with the computer specifications at hand we found major difficulties to make it work as there were many crashing and errors on the Osmosis tool. It was found that the less complicated way to work with historical OSM planet files, although highly time-consuming, was to follow the steps indicated in this small tutorial.

Glossary

System	A **system** is a group of interacting or interrelated elements that act according to a set of rules to form a unified whole (Merriam-Webster, 2022)
Risk	**Risk** is defined as the possibility or chance of potential consequences and the severity of these arising from some action or event (e.g., human-induced, natural event, or a combination of both) (Renn et al., 2011).
Systemic risk	**Systemic risks** refer to potential consequences that impact over the functionality of systems of critical importance for society and their scope in time and space. The impacts may extend beyond the system of origin to affect other systems and functions (Renn et al., 2020)
Socio-metabolic risk	**Socio-metabolic risks** are a sub-set of systemic risks 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 (Singh et al., 2020, 2022)
Tipping point	A **tipping point** is a point at which the number of small changes or incidents over a period of time reaches a level where a further small change has a sudden and very great effect on a system (Oxford University Press, 2022)
Resilience	**Resilience** is defined as the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation (IPCC, 2018)
Vulnerability	**Vulnerability** is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2022b)
Exposure	**Exposure** is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected (IPCC, 2022b)
Hazard	**Hazard** is defined as the potential occurrence of a natural or human-induced event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources (IPCC, 2022b)