3D GIS Modelling of Road and Building Material Stocks: A Case Study of Grenada

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Recent years have witnessed significant material stock accumulation within built environments, resulting in substantial environmental issues, such as greenhouse gas emissions, toxic or harmful wastes, resource scarcity, and land use conflicts. Quantitative analysis of in-use material stocks is important for assessing resource appropriation, improving the socio-economic metabolism model, and enhancing adaptive capacity to climate change. This research presents a bottom-up GIS spatial approach for modelling in-use road and building material stocks in Grenada, a small island state. LiDAR data were applied to the estimation of building heights and building stocks to improve current material stock accounting approaches. A 3D web-based application was developed to visualize material stocks in 3D building models and to enhance the understanding of the spatial distribution of material stocks. In addition, a comparative review was conducted to compare the methodological approach, results, and conclusions of this study with previous material stock studies in Grenada.

Results of this study indicate that in 2015, 4,375 kilo tonnes (40.96 t/capita) of materials were stocked within Grenada road networks, which were about one-third of that accumulated in buildings and accounted for a large share (24%) of total material stocks. Aggregates stocked within road networks occupied the largest proportion of stocks, contributing to 55% of total aggregate stocks. The considerable amount of road stocks supports the important role of materials stocked in non-building infrastructure in the context of small island states. A large proportion of road stocks were accumulated in the low-lying coastal areas, which are highly vulnerable to sea level rise. It is predicted that a sea level rise of 2.0 m would cause the majority of road stocks (over 18,187 tonnes) along the coastline of St. George’s Harbour to be inundated.

In terms of building material stocks, this study combined GIS footprint data with LiDAR elevation data to obtain the building height for each building, finding that compared with height assumptions based on occupancy classes, LiDAR-derived height estimates were closer to ground truth heights and could better represent the heterogeneity among buildings. The study for the sample site of Grenada (St. George's) demonstrates that using the inaccurate class-based height assumptions resulted in about 4.8% of overestimation in building stock estimates compared to using LiDAR-derived heights. The most discrepancy was found in concrete since concrete is the main material used in building construction. 3D building models in CityGML format and a 3D WebGIS application built on top of ArcGIS API for JavaScript were developed for Grenada integrating material stocks with the 3D city model. These 3D products can provide policy makers and practitioners with a new perspective and additional insights into material stocks and enable the public to access proprietary GIS data and material stock information through a user-friendly interface. This research serves as a pilot for assessing a novel methodology for estimating building and non-building material stocks in the context of small island states. The methodological approaches and results detailed in this research can further aid small island states in better assessing resource appropriation and evaluating their adaptive capacity to climate change.

Keywords: Material Stock Analysis (MSA), building stock, road stock, Geographic Information Systems (GIS), bottom-up, socio-economic metabolism, small island states, Light Detection and Ranging (LiDAR), 3D city model, 3D WebGIS application

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

Materialized affluent life is maintained by massive natural resources extraction. Extracted raw materials accumulating in buildings, infrastructures, and machines become in-use material stocks. In-use material stocks support the operation of a socio-economic system and ultimately flow back into the natural environment. Material stocks play an important role in socioeconomic metabolism which refers to the set of material and energy flows within and between societies (Pauliuk & Hertwich, 2015). Material stocks shape resource flows during the states of construction, use, maintenance, and disposal (Wiedenhofer, Steinberger, Eisenmenger, & Haas, 2015); therefore, playing a key role in a society's sustainable development.

It is estimated that from 1900 to 2010, global material stocks increased 23-fold due to the rapid development of human society and the economy (C. Chen, Shi, Okuoka, & Tanikawa, 2016; Krausmann et al., 2017). Significant stock accumulation in the built environment has exerted great pressure on the natural environment considering the massive resource extraction, intensive energy demand, and high greenhouse gas emissions (Krausmann et al., 2017; Nguyen, Fishman, Miatto, & Tanikawa, 2019). Sustainable and productive resource extraction, use, and disposal necessitate the quantification and mapping of material stocks that exist within socio-economic systems (De Kroon, 2020; Nguyen, Fishman, Miatto, & Tanikawa, 2019). Geographic Information Systems (GIS) is an effective and commonly-used tool to conduct spatio-temporal material stock analysis (Symmes et al., 2019; Tanikawa & Hashimoto, 2009). By employing GIS and spatial datasets, the material stocks database can be created to store and present how stocks are spatially distributed and located, and how they change over time (Nguyen et al., 2019; Symmes et al., 2019).

Although there are growing numbers of studies focusing on the material stocks and material flow analysis using GIS, few publications have taken the material stocks of non-building civil infrastructure into consideration (Marcellus-Zamora, Gallagher, Spatari, & Tanikawa, 2016; Miatto, Schandl, Wiedenhofer, Krausmann, & Tanikawa, 2017; Nguyen et al., 2019; Symmes et al., 2019; Tanikawa & Hashimoto, 2009). As one of the key non-building civil infrastructure, transportation is an important indicator to measure the economic development and the quality of social life. Nevertheless, few Material Stock Analyses (MSA) have taken into account road networks in their stock estimates, which is particularly problematic for developing countries, as these countries continually construct new roads to enable the rapid expansion of urban areas and promote the development of various industries. As such, materials stocked in roads can be important. More studies are required to investigate road stocks in the context of developing countries, as well as in the context of small island states[1]. Moreover, due to the lack of a cadastral database, developing countries and small island states often have difficulties estimating the gross volume of buildings when calculating existing building material stocks (Lanau et al., 2019; Symmes et al., 2019). This causes potential errors in the final database and stock estimates. To reduce such errors, Light Detection and Ranging (LiDAR) data could be used. LiDAR is a remote sensing technology that uses laser light to sample Earth's surface from a 3D perspective (Suomalainen, Wang, & Sharp, 2017). With the availability of LiDAR data, it is possible to estimate building heights with higher accuracy and to improve current material stock databases of developing countries and small island states.

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[1] There is no agreed criteria used to define small island states or Small Island Developing States (SIDS). They usually refer to a group of countries facing specific challenges due to their remoteness, geographic characteristics, limited resources, sensitivity to external economic or environmental shocks, and poorly developed infrastructure (Herbert, 2019; McCarthy et al., 2001). There has been some criticism of the term " Small Island Developing States (SIDS)", so "small island states" will be used in this thesis.

Most material stock estimates are reported in the form of static maps or tabular statistics outputs. Few studies have applied dynamic and interactive interfaces, such as a 3D web-based GIS, which could provide policy makers and practitioners with a 3D visualization tool for assessing material stock management and improving city planning (C. Chen et al., 2016; Koziatek & Dragićević, 2017; Tanikawa & Hashimoto, 2009).

To address such research gaps, this thesis presents a GIS-based bottom-up material stock accounting approach for a small island state (i.e., Grenada) to quantify and map building and non-building material stocks (i.e., road stocks). This new methodological approach can help improve the accuracy of current material stock accounting for Grenada by adding road stock estimation to the database and applying LiDAR data to material stock estimation. In addition, this study integrates material stocks in a 3D city model and develops a 3D WebGIS application to allow policy makers and practitioners to visually assess material stocks from a 3D perspective and provide the general public with access to the complex material stock geodatabase.

1.2 Literature Review

1.2.1 Socio-economic metabolism and material stocks

The concept of socio-economic metabolism (or social metabolism) has become an important part of sustainability science in recent years (Haberl, Wiedenhofer, Erb, Görg, & Krausmann, 2017). It is rooted in the concept of biological metabolism and is defined as a set of material and energy flows that link the society with nature and maintain the operation of a socio-economic system (González de Molina & Toledo, 2014a; Krausmann, 2018). The socio-economic system has the system boundary which defines the extent of the system. Anything inside the system boundary is considered to be domestic (Fischer-Kowalski & Hüttler, 1998). Socio-economic metabolism starts when the society extracts the raw materials from nature (input flows) and ends when the wastes and emissions are disposed back to nature (output flows). Between these two processes, there is a process in which the materials circulate and end up being consumed again (inner flow; González de Molina & Toledo, 2014b). Figure 1.1 shows a general diagram demonstrating the components and relationships that define socio-economic metabolism.

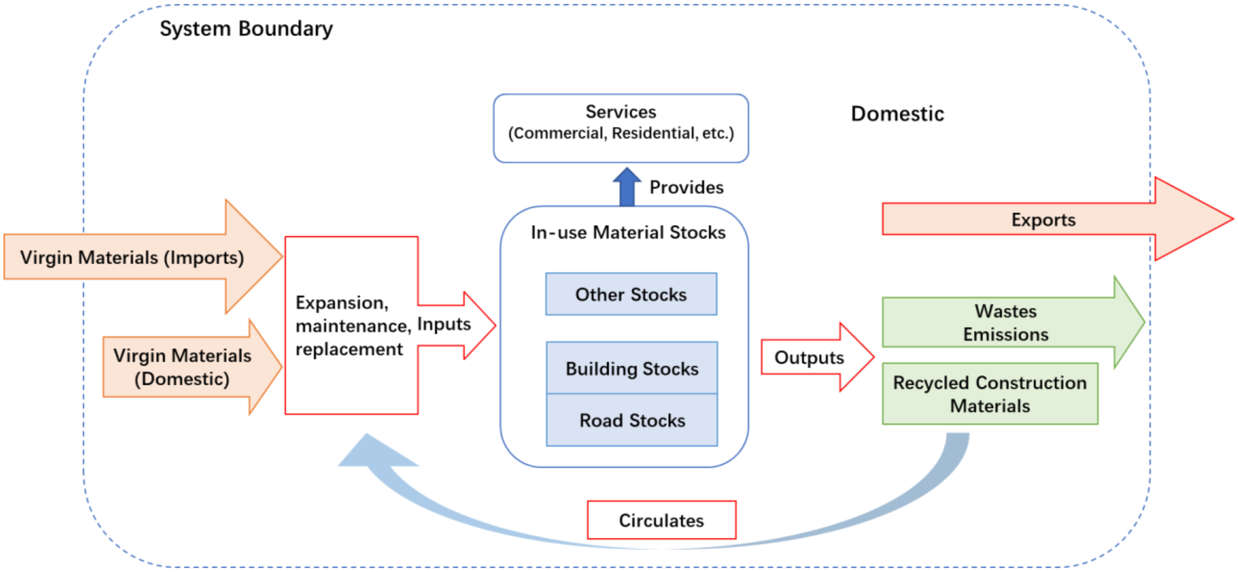

Figure 1.1: *Socio-economic metabolism conceptual diagram (modified from De Kroon, 2020; Krausmann, 2018; Wiedenhofer et al., 2015).*

Virgin materials flow into the socio-economic system for the construction and maintenance of the built environment and become in-use material stocks (MS). In-use material stocks (e.g., buildings, infrastructures) support the operation of the system by offering large numbers of services, such as shelter or dwelling, transportation, recreation, and communication. The quantity and quality of these in-use material stocks determine the quality of services and shape the resource flows during the states of construction, use, maintenance, and disposal (Fishman, 2016; Gordon, Bertram, & Graedel, 2006; Wiedenhofer et al., 2015). Therefore, gaining a better understanding and improving the management of in-use material stocks are highly important for a country's sustainable development plan. However, many countries do not consider material stock management, especially for developing countries, where rapid urbanization may be occurring. The increase of aging buildings and facilities, the immature organization for maintenance, the scarcity of data, and the intensive investment for fast infrastructure development pose significant challenges for sustainable development (Ozawa, 2008; Yashiro, 2008). Therefore, it is necessary to better understand material stocks for improving stock management, conducting material stock analyses, and developing detailed and accurate material stock databases.

1.2.2 Existing material stock accounting and analysis approaches

Material stock accounting and analysis (MSA) is an industrial ecology method that aims at investigating materials stocked within the socio-economic system (De Kroon, 2020; Fishman, 2016; Liu, Chen, Lin, & Gao, 2019). It quantifies various materials at different levels of detail, studies the spatial-temporal patterns of materials, and examines the end uses of materials (Fishman, 2016; Liu et al., 2019). In previous MSA research, two main types of analytical approaches are used: top-down and bottom-up approaches.

1.2.2.1 Top-down approaches

Top-down approaches start from an aggregated level and quantify material stocks as the sum total of net additions to material stocks (NAS; Augiseau & Barles, 2017; Kavgic et al., 2010). They place the emphasis on the material flows over time and are also referred to as "dynamic analysis". There are two main streams of top-down approaches: flow-driven accounting and demand-driven modelling (Fishman, 2016; Kavgic et al., 2010). Flow-driven accounting uses material input and output data to calculate NAS and remaining in-use materials at a single point in time (Fishman, 2016; Symmes et al., 2019). This approach allows for building a series of material stock accounts over time and even predicting future accounts (Fishman, 2016). Müller, Wang, Duval, and Graedel (2006) used the top-down approach to analyze the historical development of iron flows and storage over the period 1900–2004 in the US. The domestic production data and import and export flow data were estimated from United Nations trade statistics and statistics from different manufacturing sectors. The output data was estimated using the life-cycle assessment (Y. Zhang, 2018). Similarly, Hatayama, Daigo, Matsuno, and Adachi (2010) depicted the in-use steel stock in 42 nations by the end of 2005 and predicted the steel stock in 45 years by employing the dynamic material flow analysis approach. Noll et al. (2021) conducted the material and energy flow analysis in the context of islands and developed a complete time series (1929-2019) for socioeconomic biophysical stocks and flows in the Greek island of Samothraki. They integrated data from mixed sources (e.g., official statistics, local surveys, and previously stock-flow studies) to estimate and analyze the dynamics of socioeconomic biophysical stocks, material and energy use, and processed output for waste and emissions.

Compared with flow-driven accounting, demand-driven modelling takes socio-economic indicators into consideration and focuses on modelling the demand for materials over time (Fishman, 2016). The demand for materials is measured using the bottom-up approach (explained in the next subsection) and the outflow from stock is modelled in the same way as the flow-driven method. This approach allows for various future stock simulations and linking material stocks to society (Fishman, 2016). Müller (2006) conducted a case study in the Netherlands showing how to determine resource demands and material outflows by linking the life of materials to the population and its lifestyle.

The limitations of top-down approaches include difficulty in obtaining historical data for material flow analysis and varying data quality and reliability due to different data sources, which results in challenges in controlling the quality of resulting estimates. Demand-driven approaches require socio-economic indicators for different end-use types, which are even more difficult to obtain (Fishman, 2016; E. Müller, Hilty, Widmer, Schluep, & Faulstich, 2014; Symmes et al., 2019).

1.2.2.2 Bottom-up approaches

Bottom-up approaches start from a disaggregated level. They are built up from the inventory of end-use objects and aim at creating an account of the state of in-use material stocks (Kavgic et al., 2010; Tanikawa, Fishman, Okuoka, & Sugimoto, 2015). Since results produced by bottom-up approaches are independent from time and are essentially “snapshots” of material stock accounts, bottom-up approaches are also referred to as “static analysis” (Fishman, 2016). Bottom-up approaches compute the total amount of certain types of materials by multiplying the amount of materials stocked in each unit by the total number of units (Guo, Hu, Zhang, Huang, & Xiao, 2014). The amount of a certain type of materials in each stock unit is called the material intensity coefficient (MI) or material composition indicator (MCI). MI varies across different structures/objects but is shared within the same type or group of structures (Fishman, 2016).

A study conducted in Germany by Ortlepp, Gruhler, and Schiller (2016) extrapolated non-domestic building material stocks using the bottom-up approach. They classified the non-domestic buildings into seven types and determined the MCIs for each type based on official statistics and existing case studies. The total floor area of buildings was derived from economic data on the total amount of physical assets. Total material stocks were calculated by combining MCIs with the total floor area. Singh, Grünbühel, Schandl, and Schulz (2001) conducted the first local-level material stock study on Trinket Island and used the bottom-up approach to establish the local material stock account for two years (2000 and 2001). They classified existing infrastructure (e.g., concrete buildings, outhouses, traditional huts, wells, footpaths, etc.) on the island into ten types and developed the material intensity typology from the representative sample. The built area (i.e., physical size) of the structures was measured manually and the total stocks on the island were calculated by multiplying MI by the physical size of the structures. In addition to using statistical data on assets or conducting fieldwork to estimate the total floor area of buildings or physical sizes (e.g., total area or volume) of structures, research now uses spatial data (or geodata) in Geographic Information Systems (GIS) to conduct estimations (Gontia, Nägeli, Rosado, Kalmykova, & Österbring, 2018; Ortlepp et al., 2016). GIS refers to a computer system that gathers, manages, processes, analyzes, and presents spatial data (i.e., data referenced to locations on Earth's surface; Ortlepp et al., 2016). GIS techniques enable researchers to conduct analysis at different scales, create flexible material stock accounts, understand the spatial distribution, and compare material stocks over space and time (Lanau et al., 2019). For example, Han and Xiang (2013) used GIS in analyzing the material stock accumulation over 30 years in China. They examined the temporal changes and spatial patterns of stocked materials in different provinces during 1978-2008 using GIS and explored the driving factors behind the spatial and temporal patterns. Tanikawa et al. (2015) built a long-term material stock account of Japan using the GIS database to show how material stocks in different prefectures accumulated over time. Another research study conducted in Japan applied GIS databases and statistics to quantifying and mapping losses of building and road stocks from the earthquake and tsunami in 2011 (Tanikawa, Managi, & Lwin, 2014).

Bottom-up methods can provide detailed stock accounts but are limited in terms of information about material flows and the age of stock. Moreover, these methods are often time-consuming since extensive spatial data are required (Fishman, 2016; Lanau et al., 2019; E. Müller et al., 2014; Ortlepp et al., 2016; Symmes et al., 2019). The process of data collection also introduces uncertainties. Multiple data sources may be used so the accuracy and standard of different data may vary. It may be necessary to calculate and derive MIs/MCIs from design documents, while the overall process can be susceptible to human error. For this study, the bottom-up approach is used because it is more suitable for examining the current state of material stocks of a country that has limited historic construction datasets available and for the integration of GIS and remote sensing techniques.

1.2.3 Material stock accounting in the context of islands and the integration of LiDAR data

Although increasing numbers of studies used GIS-based bottom-up approaches to examine different types of material stocks at different scales, few studies have focused on material stocks in small island states. Small island states are a group of island countries sharing similar sustainability issues, such as the narrow resource bases, high dependence on material imports, rapid developing speed, and the vulnerability to global-scale forces (Ghina, 2003; McCarthy, Canziani, Leary, Dokken, & White, 2001; Symmes et al., 2019; Thomas, Baptiste, Martyr-Koller, Pringle, & Rhiney, 2020). These issues necessitate the implementation of efficient and sustainable extraction, use, and disposal of natural resources, which depends on the quantification and estimation of material stocks that exist within island socio-economic systems.

As mentioned in the previous section, bottom-up approaches calculate the material stock amount based on two main databases: the physical size of the objects and the MI/MCI specific to each object (Gontia, Nägeli, Rosado, Kalmykova, & Österbring, 2018). However, these databases are not available in many countries or require a long period of time to collect and develop, especially for non-building infrastructures which have diversified functions and components (Lanau et al., 2019). Thus, research on material stock accounting and analysis is limited for small island states, and non-building infrastructures, such as roads, have seldom been taken into consideration in current material stock accounts of small island states (Augiseau & Barles, 2017; Bradshaw, Singh, Tan, Fishman, & Pott, 2020; De Kroon, 2020; Miatto et al., 2017; Nguyen et al., 2019; Symmes et al., 2019). Previous studies on road stocks mainly focused on some of the world’s large economies such as China (Guo, Hu, Zhang, Huang, & Xiao, 2014; Han & Xiang, 2013), Japan (Tanikawa et al., 2015, 2014), US (Miatto et al., 2017), and EU25 (Wiedenhofer et al., 2015). One recent study analyzed the material stock of roads in Vietnam, which showcases the possibility and feasibility of road stock accounting in a developing country (Nguyen et al., 2019). Noll, Wiedenhofer, Miatto, & Singh, (2019) applied the bottom-up stockdriven approach to the dynamic modelling of in-use stocks in the context of an island (the Greek island of Samothraki) from 1971 to 2016. They estimated the materials stocked in buildings, roads, ports, and the sewage system and modelled the material flows related to the construction, maintenance, and demolition processes. Both Nguyen et al. (2019) and Noll et al. (2019) used reported statistics from official or unofficial sources to estimate the physical size of roads instead of using GIS techniques. More studies need to be conducted exploring developing countries and specifically, small island states, and GIS techniques should be utilized to improve the spatial resolution and strengthen the understanding of the composition and spatial distribution of material stocks, especially non-building stocks.

Limited data availability and resources in small island states not only limit the type of material stock analysis but also introduce uncertainties to the current material stock accounting approach for small island states. As explained in the previous section, the bottom-up approach calculates the material stock by multiplying the MI by the physical size of the structure. In terms of roads, the physical size is dictated by length or area, which could be derived from GIS data, government statistics, design standards, or fieldwork (Miatto et al., 2017; Nguyen et al., 2019). In terms of buildings, the physical size could be represented as the gross floor area (GFA) or gross volume (GV). GFA could be calculated from building footprints and GV requires both floor area and building height (Stephan & Athanassiadis, 2017). Using GFA assumes that the building height, as well as the building structure, are the same or similar within a specific occupancy class. This assumption is generally acceptable for areas with high homogeneity or for making an estimation at a large scale (De Kroon, 2020; Stephan & Athanassiadis, 2017). However, GFA ignores the vertical assemblies and the heterogeneity among buildings, which affects the accuracy of the physical size estimation and material stock account estimates (Schebek et al., 2017; Stephan & Athanassiadis, 2017). GV can better capture the building geometry and possibly improve the accuracy of material stock estimates. If building height information is available, researchers would tend to use GV rather than GFA (Schebek et al., 2017; Stephan & Athanassiadis, 2017; Symmes et al., 2019). Nevertheless, building height information is not available in many study areas, especially in developing countries or small islands, since LiDAR data collection, processing, and management can be a time-consuming and expensive endeavor. Therefore, only GFA was considered in previous material stock studies for small island states. Although small island states are increasingly investing in LiDAR data surveys and inquisition, they often do not know how to process or utilize such large datasets. The increasing availability of LiDAR in developing countries may be used to adjust and enhance material stock accounting estimates.

Light Detection and Ranging (LiDAR) has proven to be a powerful remote sensing technology with a range of applications for analyzing civil infrastructure. The inherent 3D nature of LiDAR data (i.e., LiDAR point cloud) enables them to be utilized in the 3D construction of city objects, such as buildings (Abdullah, Awrangjeb, & Lu, 2014; Alexander, Smith-Voysey, Jarvis, & Tansey, 2009; Kaye Villanueva et al., 2015; Park & Guldmann, 2019). Using LiDAR data to estimate building heights requires the definition of building edges or boundaries (i.e., the extent of each building). Building edges can be extracted from satellite images and/or LiDAR data, but these methods are not very efficient. Using existing building footprint polygons as building edges could highly reduce the computational and labour cost, especially when generating large-scale building models (Abdullah et al., 2014; Alexander et al., 2009; Lingfors et al., 2017; Mishra & Zhang, 2012; Xiong, Oude Elberink, & Vosselman, 2016).

When utilizing footprint polygons as building edges, LiDAR points within footprints can represent building rooftops and building heights can be obtained from these 3D height measurements (Alexander et al., 2009). However, the points within footprints can vary in accuracy due to various sources of error. Irrelevant points that represent the ground, cars, and small indentations can potentially be included (Awrangjeb & Fraser, 2014; Park & Guldmann, 2019). Extraneous objects, such as trees, chimneys, and spikes that hang over rooftops may also introduce a source of noise (Amolins, 2016; Awrangjeb & Fraser, 2014). Moreover, the LiDAR aircraft not only scans the tops of objects but also scans the sides, including parts of building walls (Park & Guldmann, 2019).

Therefore, the critical challenge in this methodology is to remove irrelevant points and extract only those that coincide with rooftops for estimating building heights. Some studies use buffer analysis to identify noises and to remove them; for example, Qiu et al. (2010) created smaller buffers inside the footprint boundary to exclude extraneous points from surrounding ground and walls and used the median height of points inside the buffer to represent the rooftop height. The problem with such methods is that they cannot effectively and accurately remove all errors, especially noise within footprints (e.g., skyscrapers, trees, hanging objects, etc.) or noise from neighbour footprints that border the current footprint. Park and Guldmann (2019) proved that using the footprint-buffer method could introduce even higher errors into height estimates compared to not using any methods at all, especially when the accurate ground height is not available. Some studies use specified criteria to filter out irrelevant points; for example, Awrangjeb and Fraser (2014) used differences in heights as a rule and removed points that had greater differences relative to the average of neighbours. Villanueva, Ang, Inocencio, and Rejuso (2015) used height, slope, terrain ruggedness, and area as criteria to separate points other than those on rooftops. A downside of such methods is that it is difficult to decide on a suitable threshold based on the study area that would omit erroneous points while capturing those that coincide with actual rooftops. Decreasing the threshold may include excessive irrelevant points, while increasing the threshold may misclassify outliers within the footprint as rooftop points.

Park and Guldmann (2019) introduced an improved and generalizable methodology that uses a machine learning technique called random forest (RF) to classify the LiDAR point cloud. The points were classified as roof, wall, high outlier, and ground, based on several measures/features (e.g., point features, footprint features, and point-neighbour features) of training data. The median or mean heights of rooftop points served as the building heights. The results of their study demonstrated that using a RF classifier to classify the point cloud can improve the accuracy of height estimates; however, this method is based on the ground truthing of the training samples in order to train and test the classifier. The sampling of ground truth points requires high-resolution orthorectified aerial images, street views, and 3D imagery to identify points of different classes, which is not feasible for some study areas with limited data availability.

1.2.4 Vulnerability of transportation infrastructure in the context of island and sea level rise vulnerability mapping

Sea level rise (SLR) and extreme weather events have posed a large threat to the livelihoods and the socio-ecological system of island nations (Petzold & Magnan, 2019; United Nations Framework Convention on Climate Change (UNFCC), 2007). Among all nations which suffer from the adverse effects of climate change, small island states are the most vulnerable due to their remoteness, low availability of resources, high civil infrastructure costs, and susceptibility to natural disasters (Merschroth, Miatto, Weyand, Tanikawa, & Schebek, 2020; United Nations Framework Convention on Climate Change (UNFCC), 2007; United Nations Framework Convention on Climate Change (UNFCCC), 2005). For small island states in the Caribbean, it is reported that the tropical cyclone season in 2017 has caused over $5.4 billion USD economic loss in only five of the affected countries. Approximately three million people were displaced in 16 countries (ECLAC, 2018; Internal Displacement Monitoring Centre (IDMC), 2018; Thomas & Benjamin, 2020). In addition, as one of the main economic sectors of small island states, the tourism sector is now facing the threat of global sea level rise (SLR). It is estimated that 29% of the resort properties in 19 Caribbean Community countries would be partially or fully exposed to 1 meter SLR and over 49% of the resort properties would be affected by beach erosion (Scott, Simpson, & Sim, 2012).

1.2.4.1 Vulnerability of transportation infrastructure in the context of island states

Among all the aspects of life in small island states , transportation is the sector that is highly sensitive and vulnerable to risks from climate change (Unctad, 2014; World Bank, 2017). Due to the unique spatial characteristics of small island states, large quantities of transportation infrastructure and related operations are located in disaster-prone areas close to the shoreline, which are vulnerable to extreme weather events and sea level rise. In a disaster event, transportation disruptions can obstruct access to critical services (e.g., water, electricity, health clinic, waste management, etc.) and result in massive socio-economic losses (UNOPS & Univerisity of Oxford, 2020;World Bank, 2017, 2019). The lack of alternative transport options in small island states can also impede the disaster relief and recovery process (World Bank, 2019).

Constrained by the limited availability of financial and human resources, small island states lack the capacity to assess vulnerability and build adaptation and resilience in terms of coastal transportation infrastructure (UNCTAD, 2018). Therefore, it is necessary for small island states to carry out vulnerability assessments to identify coastal areas at risk and to develop adaptation plans (Monioudi et al., 2018). Vulnerability refers to ‘the degree to which systems are susceptible to, and unable to cope with, adverse impacts’ (IPCC, 2007, p.48). Previous research has conducted some analyses assessing the vulnerability of small island states to scenarios of climate change; for example, Scott et al. (2012) assessed the vulnerability of Caribbean coastal tourism to SLR by overlaying the inundated coastal pixels in Digital Terran Model (DTM) with coastal resort locations. Monioudi et al. (2018) evaluated the potential climate impacts on coastal airports and seaports in Jamaica and Saint Lucia under a 1.5℃ specific warming level condition. Giardino, Nederhoff, and Vousdoukas (2018) assessed the effects of flooding and coastal erosion on the island of Ebeye (The Republic of the Marshall Islands). They estimated the expected damages and affected people under multiple hazards by combining inundation maps, exposure data, land value data, and a depth-damage function describing the relationship between flood depths and damages. Despite a growing number of studies dedicated to assessing climate impacts on different aspects in small island states, few of them have focused on socioeconomic metabolism and material stocks, especially stocks within the transportation infrastructure, such as roads. Even fewer studies generated detailed vulnerability maps with high accuracy (Cooper, Fletcher, Chen, & Barbee, 2013; Monioudi et al., 2018; UNCTAD, 2018). Symmes et al. (2019) analyzed the vulnerability of building material stocks to extreme weather events and SLR scenarios in Grenada, one of the small island states. Similarly, Bradshaw et al. (2020) assessed the vulnerable building stocks under 1 m and 2 m SLR scenarios in another small island state, Antigua and Barbuda. Material stocks in roads were not assessed in these two studies and the Digital Elevation Models used were in coarse horizontal resolution and had high vertical uncertainties.

1.2.4.2 Sea level rise vulnerability mapping

Sea level rise (SLR) as one of the major effects of climate change has aroused international awareness in recent years (Mimura & Horikawa, 2013). The accelerating rate of SLR compels researchers to generate accurate vulnerability or risk assessments and comprehensive adaptation plans (Cooper et al., 2013; Giardino et al., 2018). SLR vulnerability mapping is a type of hazard risk mapping utilizing GIS techniques to show assets at risk. Generating reliable SLR vulnerability maps can help identify sensitive areas, assess the expected damages and affected population, and improve planning for resilient infrastructure.

Current vulnerability mapping for small island states is mainly based on global DEMs with coarse resolution such as Shuttle Radar Topography Mission (SRTM) DEM, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM, and Global 30 Arc-Second Elevation (GTOPO30; Ryan Sim, 2011; Scott et al., 2012; Rob Symmes et al., 2019). Some of the DEMs are integrated with Light Detection and Ranging (LiDAR) products to gain higher resolution and accuracy (such as the DEM for the main island of Saint Vincent; Knowles et al., 2015). However, due to the limited accessibility of LiDAR data in small island states, the majority of the DEMs are in coarse horizontal resolution (e.g. 5 m, 10 m, 30 m), which introduces more mapping errors and is not suitable for generating detailed vulnerability maps (Cooper et al., 2013; Kettle, 2012; Martyr-Koller, Thomas, Schleussner, Nauels, & Lissner, 2021; K. Zhang, Dittmar, Ross, & Bergh, 2011). The lack of metadata for the DEMs for small island states is another source of uncertainty in the final products. In recent years, increasing numbers of local governments of small island states have realized the benefits of LiDAR products and have flown LiDAR surveys at the national scale. Access to LiDAR data is increasingly becoming a possibility. Therefore, to improve the quality of the SLR mapping in small island states, DEMs or DTM derived from LiDAR ‘ground’ returns can potentially be used by decision makers to identify high-resolution SLR vulnerable areas and form management guidelines more effectively.

To accurately map SLR, the ground surface and the water surface are needed. The ground surface refers to DEM or DTM and serves as the base layer for mapping inundation. The water surface refers to the interface between water and air and represents the original sea level (Coastal Services Center, 2012). The water surface can be derived from existing water models, interpolated water surfaces, or single value water surfaces (Coastal Services Center, 2012). Existing water models are the hydrodynamic models and wave models developed from previous tide gauge observations during past extreme weather events. These models are available for many developed countries (e.g., SLOSH model for the U.S.) but not for small island states (Coastal Services Center, 2012). Water surfaces interpolated from known data points (e.g., water level and tide gauges) are a second available option but for many small island states, such as Grenada, up-to-date and detailed water level data may not exist (Coastal Services Center, 2012; Giardino et al., 2018). Thus, a third option is to create a single value water surface, which represents the water level for an entire study area. This single value can be obtained from atmospheric models, measurements from tide or water level gauges, or other empirical models (Coastal Services Center, 2012). With the single value of water surface level, the flooded or inundated zones can be identified following a “bathtub” approach in which a grid cell is identified as inundated if its height is below the given sea level scenario and is hydrologically connected to the sea (Breili, Simpson, Klokkervold, & Ravndal, 2020; Gesch, 2009). The “bathtub” approach is widely used in coastal inundation mapping because of its simplicity and low computational cost. However, this simplistic method ignores the integrated and dynamic responses of the hydrodynamics, coastal morphology, and marsh ecology to SLR, which may affect the accuracy of the inundation mapping at local scales (Breili et al., 2020; Passeri et al., 2015).

1.2.5 3D city model

3D city models have become increasingly important in today’s realization of city projects including visualization for navigation, 3D cadastre, urban planning, communication of urban information to citizenry and other non-visualization or visualization-based applications (Biljecki, Stoter, Ledoux, Zlatanova, & Çöltekin, 2015a; Janečka, 2019). A comprehensive and state-of-the-art review of diverse 3D city models applications was provided by Biljecki et al. (2015). As discussed in Section 1.2.1, material stock management is critical for a city’s sustainable development. The integration of 3D city models and a material stock database could be a new application that visualizes material stocks spatial distribution from the 3D perspective, assesses vulnerable material stocks, supports material stock management, enhances decision making, and strengthens the communication of material stock information between municipal administrations and citizens.

Currently, the CityGML standard is the most critical international standard and exchange format for 3D geospatial data (Janečka, 2019). It classifies the spatial objects into five standardized Levels of Details (LoDs) based on geometry. Since buildings are the main objects visualized in 3D in this study, the main types of 3D building models are described in Table 1.1 below.

Table 1.1: *Main types of 3D building models according to the Open Geospatial Consortium (OGC) standards (Gröger, Kolbe, Nagel, & Häfele, 2012; Gröger & Plümer, 2012; Park & Guldmann, 2019).*

3D building model	**Description**
LoD0	- 2.5D Digital Terrain Model with a map or satellite image as the base map. - Buildings are shown as footprints polygons.
LoD1	- Block-shaped building model with a certain height and flat roof.
LoD2	- Building model representing multiple roofs with different shapes and heights.
LoD3	- Building model precisely reflecting the real architecture and detailed surface structure.
LoD4	- Building model precisely reflecting the real architecture including the interior structure.

Examples of the five LoDs are shown in Figure 1.2. The LoD1 model is the most widely used, whilethe LoD2 or higher-level models could be realized if further geoinformation is available (Park & Guldmann, 2019; Xiong et al., 2016). Researchers have also proposed the LoD1+ model which has subdivisions in the building footprints and can represent different roof heights (Park & Guldmann, 2019; Xiong et al., 2016).

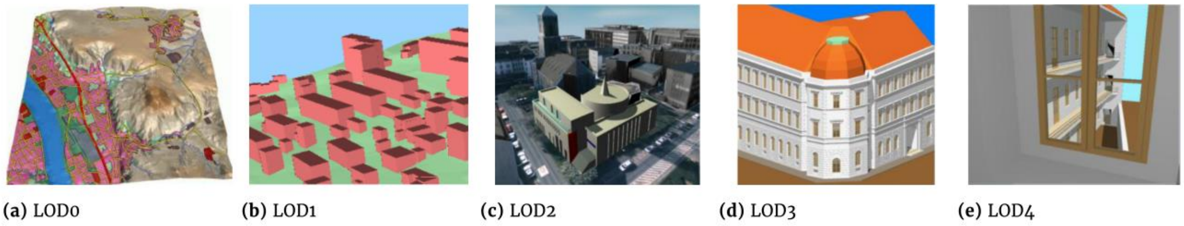

Figure 1.2: *Five level of details for buildings defined by CityGML (Gröger et al., 2012).*

Systems that support CityGML and 3D visualization do not have to be information systems designed for the public. Such systems can deliver 3D city models but cannot be used easily to interact with the models and to ask simple queries such as: how tall is the building? What is the name of the building (Flick & Coors, 1998; McCord, Tonini, & Liu, 2018)? To view and explore city models, users are required to have technical knowledge and access to specialized software, which are not always possible (Flick & Coors, 1998; Gkatzoflias, Mellios, & Samaras, 2013). Therefore, developing a web-based application that does not require a large amount of GIS knowledge from the side of users is an asset. The web-based GIS application enables users to access proprietary GIS data over the internet and interact with the 3D models through a user-friendly interface (Gkatzoflias et al., 2013). It empowers municipal administrations and citizens to get close to 3D city models and comprehensive information (e.g., building information, material stock information, etc.), while encouraging public participation in city planning. Although the internet provides the web-based GIS application with accessibility and interactive powers, the massive amount of data transmission could exert a significant burden on network connections and limit the application performance (De Paiva & Baptista, 2009; Peng & Tsou, 2003). Reducing the number of web transactions or the volume of data transmission between servers and clients could aid in the application performance but may trade away the precision (Yang, Wong, Yang, Kafatos, & Li, 2007).

1.3 Research Goals and Objectives

A few studies have investigated material stocks using GIS-based bottom-up approaches in the context of small island states; however, they did not take road stocks into consideration and did not use actual building heights when estimating building stocks. In addition, previous material stock research has not attempted to integrate material stocks with 3D city models and develop WebGIS applications to aid in visualizing the state of material stocks. This thesis builds on previous research conducted by De Kroon (2020) and Symmes et al. (2019) and sets out to enhance their methodology and estimates by incorporating road material stocks and to address current research gaps. The research goals are to develop a more comprehensive material stock accounting approach for small island states and to develop a web-based product that integrates 3D city models and material stock estimates.

This thesis adopts a manuscript style, consisting of two manuscripts that will be prepared for publication. The first manuscript (Chapter 2) intends to develop a GIS-based bottom-up approach for Grenada to quantify materials stocked in the road network and assess vulnerable coastal road stocks. The main objectives of this study are three-fold:

1. To estimate in-use road material stocks in Grenada and identify the spatial distribution of road material stocks.

2. To assess the effect of including road material stocks on total estimated material stocks in Grenada.

3. To evaluate services associated with roads and assess road material stocks vulnerable to potential sea level rise (SLR) in the future.

The second manuscript (Chapter 3) seeks to investigate building material stocks in Grenada from a 3D perspective by utilizing LiDAR data in material stock estimation and develop a 3D WebGIS application linking material stocks to 3D city models. The main objectives of this study are four-fold:

1. To estimate building heights for individual buildings utilizing LiDAR data and recalculate building material stocks.

2. To conduct an accuracy assessment of the building material stocks.

3. To develop 3D building models and a WebGIS application to visualize the material stock account of a small island state case study.

4. To compare the methodological approach, results, and conclusions of this study with previous material stock studies in Grenada.

1.4 Study Area

The study area is Grenada, a small island state located in the West Indies in the Caribbean Sea (Symmes et al., 2019). It has an area of 344 square kilometers and a population of 112,417 according to recent United Nations data (Worldometer, 2020). It consists of three islands: the main island of Grenada (as shown in Figure 1.3), and two smaller islands, Carriacou and Petite Martinique. The main island of Grenada is the main study area.

The tertiary sector, generally referred to as the service sector, is the most important economic sector of Grenada. It accounted for 82.1% of GDP in 2017 and 81.8% in 2018 (Bradley, 2019; Donnelly, 2019). Within the tertiary sector, the travel and tourism sector is a leading contributor to GDP and constituted 40.5% of Grenada's GDP in 2020 before the COVID-19 island-wide lockdown (Caribbean Development Bank, 2021). Grenada's strong and solid economic performance in recent years is highly dependent on the continued growth in tourism. In 2018, the figures for total visitors and expenditure increased by 12.8% and 10.1%, respectively (Donnelly, 2018, 2019). The tourism boom results in increasing investment in hotel resorts and other accommodations. The materials imports have surged due to the construction of these accommodations and other infrastructure projects such as the expansion of St. George's University (Donnelly, 2019).

Grenada is extremely vulnerable to the adverse impacts of climate change because of its remoteness, limited resources, and special socio-economic characteristics (Merschroth et al., 2020; United Nations Framework Convention on Climate Change (UNFCC), 2007). It highly relies on climate-sensitive socio-economic activities. Most of the important activities are concentrated in the coastal areas since critical infrastructures and the majority of the population are located along their coasts (Merschroth et al., 2020; Peters & Smith, 2001). Therefore, sea-level rise and extreme weather events pose a serious threat to the low-lying coastal areas. It is projected that due to beach and shoreline loss, the reconstruction and recovery costs in Grenada tourism industry will account for 12.4 % to 21.5 % of GDP in 2050 (Simpson et al., 2010). In order to gain sustainable development and improve adaptive capacity to climate change, the management of in-use material stocks is necessary for Grenada. Improved understanding of the quantity and distribution of material stocks on the island will enable better management of material stocks and flows, which are relevant for sustainable development and planning.

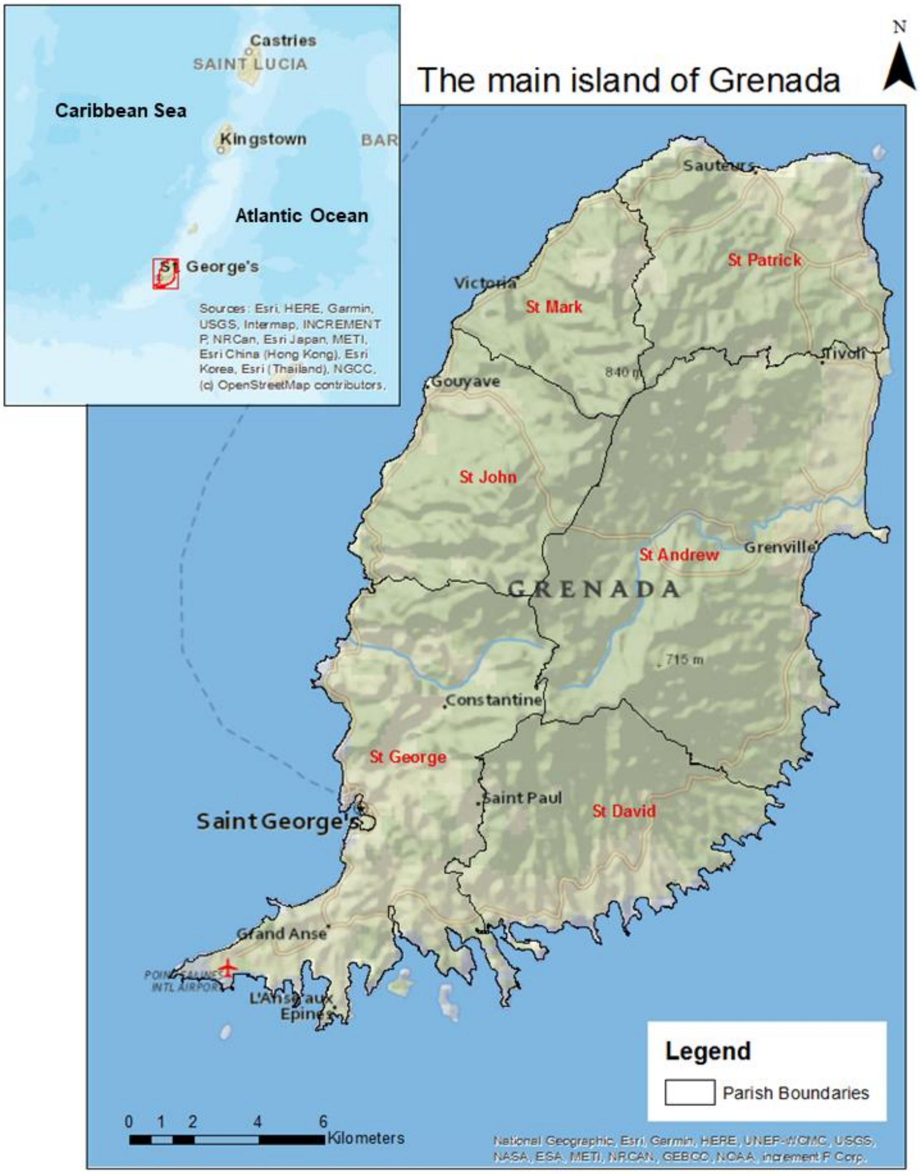

Figure 1.3: *The main island of Grenada with parish boundaries.*

1.5 System Boundary and Data Source

Before estimating and analyzing material stocks, the system boundary of the socio-economic system should be established to define what is inside or outside a socio-economic system. For a country, the geographic boundary of the national territory is considered as the system boundary and anything inside the country boundary is considered domestic. Materials that flow into the country are imports, while materials that leave the country are exports. All materials stocked within the system and being used by humans during a given time period are considered to be in-use material stocks (Gerst & Graedel, 2008; Krausmann, 2018; Symmes et al., 2019; Wiedenhofer et al., 2015). In this research, the system boundary is the geographic boundary of the main island of Grenada, and the analysis focuses on a subset of in-use material stocks: building stocks and road stocks. The types of materials for buildings include concrete, timber, aggregate, and steel; materials for roads include aggregate, cement concrete (a mixture of cement and aggregates, excluding roadbed), and asphalt concrete (a mixture of asphalt and aggregates, excluding roadbed).

To conduct material stock accounting and spatial analysis, spatial data including road network vector data, boundary vector data, building footprint data, building stock data, land cover data, and elevation data were required. These spatial data were cleaned, checked, and stored in a geodatabase for Grenada created in the previous studies (De Kroon, 2020; Symmes et al., 2019). Appendix A shows the full metadata catalog for this geodatabase. Major spatial data used in this study are listed in Table 1.2. Road network data were used to classify the road network and calculate road material stock. Building footprint data containing the building material stock and service information were developed from the previous studies (De Kroon, 2020; Symmes et al., 2019) and were used to recalculate and visualize the building material stock integrating with LiDAR data. LiDAR data were also employed to develop the Digital Terrain Model (DTM) for assessing vulnerable road stocks located along the coast. Road network data, building footprint data, river data, transportation port data, boundary data, and the land use map for Grenada were the components of the web-based 3D maps.

Table 1.2: *Data sources.*

Data	Type	Year	Attributes	Extent	Source
Road network	Shapefile	2015	Polyline, general road type	Grenada	Caribbean Handbook on Risk Information Management (CHARIM)
Road network	Shapefile	2020	Polyline, general road type, pavement material	Grenada	Open Street Map
Land cover map	Shapefile	2009	Land use	Grenada	Ministry of Agriculture, Government of Grenada
Building footprints	Shapefile	2014	Polygon, use type, occupancy class, material intensity, number of stories, material stocks, field work photo	Grenada	CHARIM, and previous research (De Kroon, 2020; Symmes et al., 2019)
Parish boundaries	Shapefile	Current	Polygon, boundaries	Grenada	CHARIM
Country boundaries	Shapefile	Current	Polygon, boundaries	Grenada	CHARIM
Census enumeration districts	Shapefile	Current	Polygon, boundaries	Grenada	CHARIM
LiDAR data	Laz	2017	LiDAR point cloud including the elevation information (Nominal Point Density: ~11 pts/m^2, Accuracy (1 sigma): <10 cm in Z, <10 cm in XY)	St. George's	Land Use Division, Ministry of Agriculture, Government of Grenada
Digital Elevation Model (DEM)	Raster	2016	Elevation data	Grenada	CHARIM

River	Shapefile	2016	Polyline	Grenada	CHARIM
Transportation ports	Shapefile	2016	Polygon, airports, and seaports	Grenada	CHARIM

The software used in this study includes ArcGIS, ArcGIS Pro, ArcGIS Online, ArcGIS API for JavaScript, Whitebox Geospatial Analysis Tools, LAStools, and FME. The series of GIS tools (ArcGIS, ArcGIS Pro) were employed for the material stock analysis and rough LiDAR data processing. Whitebox Geospatial Analysis Tools and LAStools were utilized to further process LiDAR data and create LiDAR data products. FME was the tool for converting data formats. ArcGIS Online and ArcGIS API for JavaScript version 4.21 for were the main tools used for creating web-based 3D maps.

1.6 Thesis Structure

This thesis follows a manuscript design and consists of one introductory chapter (Chapter 1), two manuscript chapters (Chapter 2-3), and one concluding chapter (Chapter 4). Chapter 1 introduces the research and provides a literature review discussing research context, existing research, research gaps, and the rationale for the research. An overview of research goals and objectives and an introduction to the study area and data sources are also included in Chapter 1. Chapter 2 and 3 are two independent manuscripts contributing to this thesis; the former manuscript focuses on estimating and analyzing the materials stocked in Grenada road network, while the latter aims to explore building material stocks from a 3D perspective and develop a 3D model and web-based application. Chapter 4 highlights and discusses the findings and conclusions of the study, as well as recommendations for future research, material stock management, and sustainable development in small island states.

Chapter 2

The Links Between Transportation and Material Stocks: GIS modelling of Road Material Stocks

2.1 Introduction

Transportation infrastructure is vital for small island states' internal and external trade and mobility. A sustainable and well-maintained transport sector can provide people with reliable linkages to essential goods, services, and opportunities, thereby promoting economic growth and improving the quality of life (Asian Development Bank (ADB), 2017; Parkash, 2007; Unctad, 2014; World Bank, 2017). As one of the key components of non-building civil infrastructure, modern transportation infrastructure is material-intensive, which exerts tremendous pressure on the natural environment during the stage of resource extraction, maintenance, and disposal. How to properly manage and recycle these material stocks is a key issue that needs to be resolved when planning for sustainable development (Miatto et al., 2017; Nguyen et al., 2019). The establishment of management strategies requires a comprehensive understanding of the status of in-use stocks, which necessitates the quantification and mapping of material stocks in transportation infrastructure, especially road networks. Nevertheless, road material stock accounting is not the focus of current material stock research and few studies have investigated road stocks in developing countries, especially small island states. This study aims to develop a GIS-based bottom-up approach for the small island states case study of Grenada to quantify in-use road material stocks and assess the effects of including such stocks in current material stock estimates for Grenada. This study also seeks to assess the relationships between road stocks and their supporting services and to assess the vulnerability of road stocks in coastal areas, which are vulnerable to the effects of climate change.

2.2 Methodology

This section describes and explains the methodological approach adopted to address the objectives of this study. The general methodology workflow is shown in Figure 2.1. Each step in the diagram is explained in more detail within the subsequent methodology sections. The road classification system and road material stock accounting approaches employed for the case study of Grenada are explained in Section 2.2.1. Section 2.2.2 assesses the impact of the inclusion of road stocks in total material stock estimates. Sections 2.2.3 and 2.2.4 present the methods used to evaluate services associated with roads and identify road stocks that are vulnerable under future sea level rise scenarios.

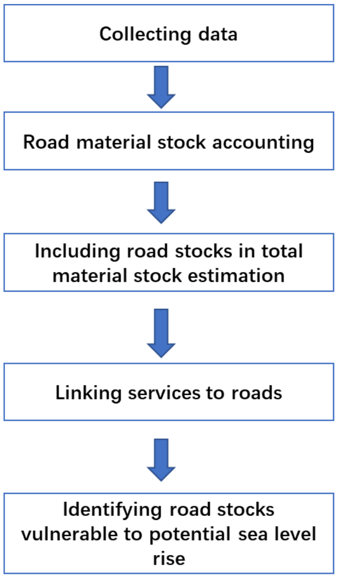

Figure 2.1: *Methodology workflow for assessing vulnerable road stocks to sea level rise.*

2.2.1 Methodology of road material stock accounting

The overall methodology of material stock accounting and analysis used in this study is classified as a bottom-up approach as discussed in Section 1.2.2. Figure 2.2 below illustrates the overall workflow, and the following subsections detail the specific methodological approaches used in the case study of Grenada. The road network in Grenada was first categorized into different road types (Section 2.2.1.1) and assigned specific road widths and material intensities (Section 2.2.1.3). These material intensities were then used along with the gross area of roads (Section 2.2.1.2) to quantify the volume of different materials stocked within the road network (Section 2.2.1.4). GIS techniques were used to approximate road length measurements, analyze the spatial distribution of road stocks, and improve the current transportation geodatabase for Grenada.

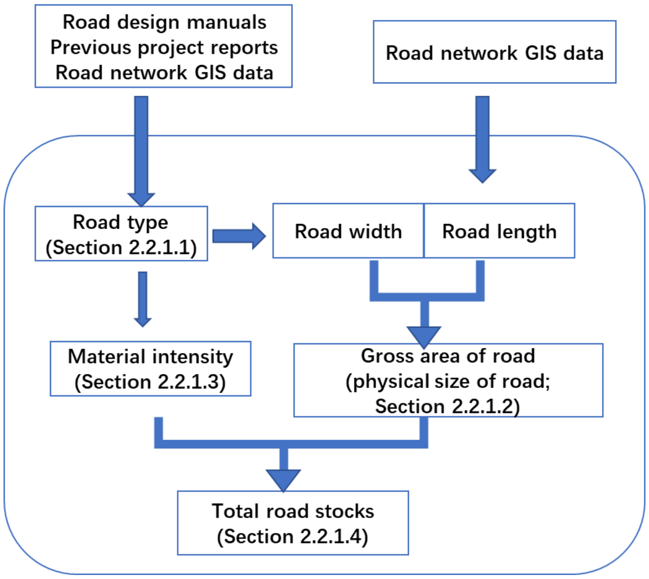

Figure 2.2: *Workflow of road material stock accounting.*

2.2.1.1 Road classification

To calculate road stocks, the first step was to classify roads into different road types and assign each road type specific road widths and material intensities. In general, roads are usually classified in a hierarchical manner based on their functions within a transportation system. Road functional classes are designated according to the intended purpose of the road, i.e., to provide priority for property access or traffic mobility (as shown in Figure 2.3). Higher-level roads (e.g., expressways and arterials) tend to have higher mobility and lower accessibility, while lower-level roads (e.g., collectors and local roads) tend to have higher accessibility and lower mobility (Toronto Transportation Services, 2013; U.S. Department of Transportation Federal Highway Administration, 2017b).

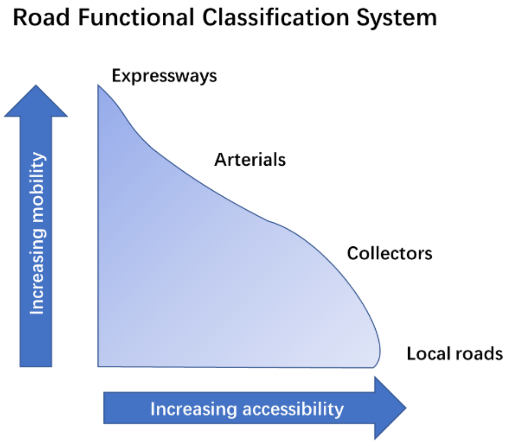

Figure 2.3: *Road functional classification system (AASHTO, 2018; U.S. Department of Transportation Federal Highway Administration, 1992).*

The road geometric design standard is consistent with the road functional classification and specifies the dimension and arrangement of geometric features of each road class, including road widths, shoulder widths, reservation distances, sag curves, and other features (Ministry of Transportation, 1985; U.S. Department of Transportation Federal Highway Administration, 2020). Roads in the same functional class share similar geometric characteristics (e.g., road widths) but may have different pavement structures (e.g., rigid concrete pavement, flexible asphalt pavement, and unpaved) depending on the local environment, local service requirements, short- and long-term costs, and impacts to the public (Toronto Transportation Services, 2019). Different pavement structures result in different material compositions and different material intensities (MI). In bottom-up material stock analysis, a fundamental assumption is that each road type shares the same material intensity and road width. The road widths are then used to calculate the road surface area, which are combined with material intensities to estimate the total road material stocks. Therefore, for the purposes of conducting a material stock analysis, the road functional classes were further classified into several road types based on the pavement structures and each road type shares the same road width and material intensity. The final road classification system for Grenada in the form of a decision tree is shown in Figure 2.4 below and is detailed in following Sections 2.2.1.1.1 and 2.2.1.1.2.

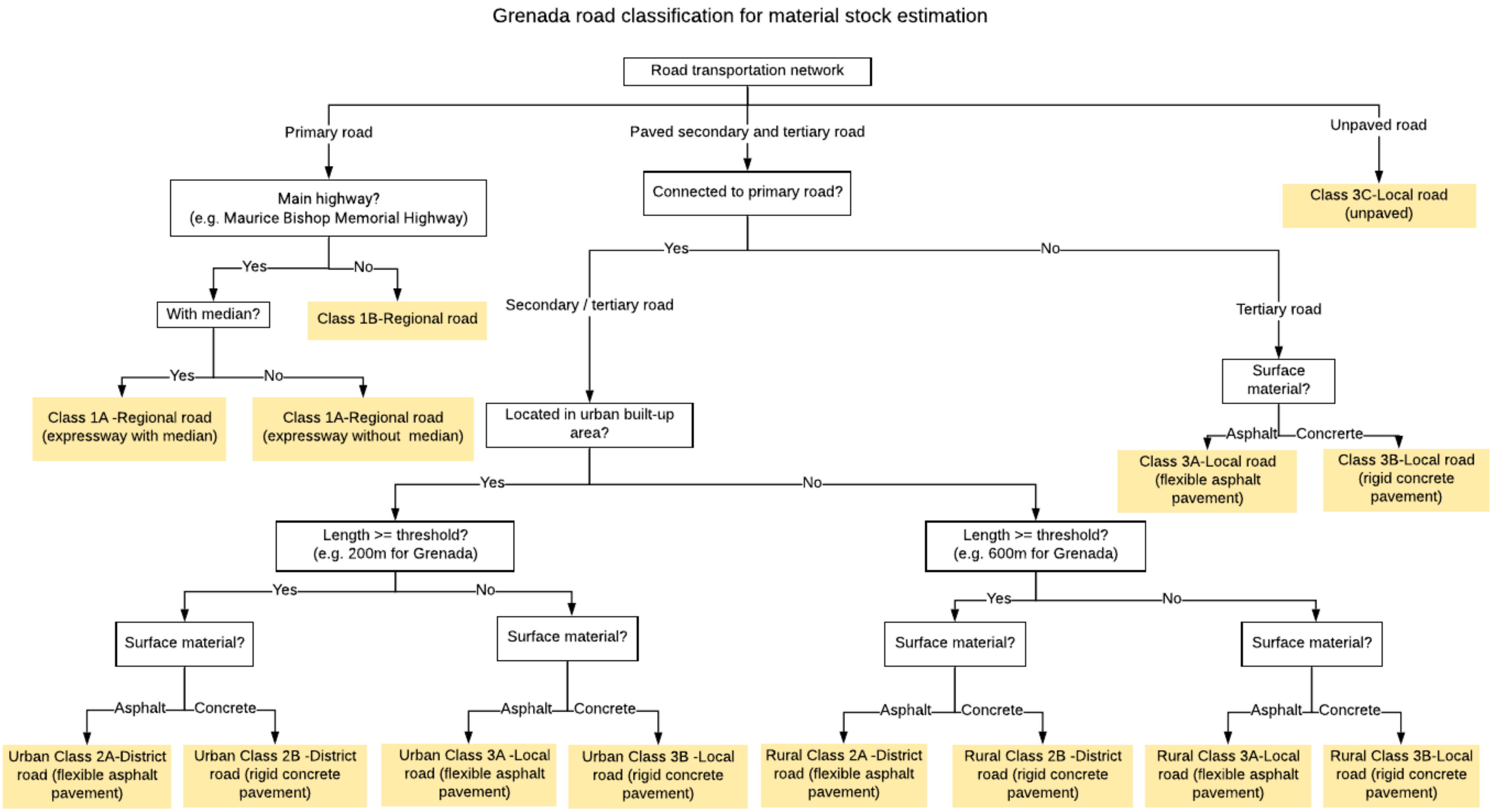

Figure 2.4: *Grenada road classification system used for material stock accounting.*

2.2.1.1.1 Road classification based on functions

The first step in road classification was to generate a basic road hierarchy that classifies roads according to their functions. Functional classification defines the intended use of different road classes and supports the selection of design speed, which aids in the establishment of geometric design elements, such as the road width, horizontal alignment, and vertical alignment (Wolhuter, 2015).The basic hierarchy comprises of freeways/expressways, arterials, collectors/district roads, and local roads. Expressways and arterials consist of roads of national importance and have the highest mobility and limited access to property. Collectors and local roads are comprised of roads of regional importance and local importance and have higher accessibility and lower mobility (Toronto Transportation Services, 2013; U.S. Department of Transportation Federal Highway Administration, 2017b). Grenada does not have an up-to-date and uniform road classification system, which differs between ministries (Grenada Ministry of Infrastructure Development, 2020). In this study, Grenada’s basic road hierarchy was derived from the road classification used by Ministry of Infrastructure Development, Public Utilities, Energy, Transport & Implementation (MOT/MOID), Government of Grenada. The road functional classification used by MOT follows the Roads Act Chapter 290 of the 1994 Laws of Grenada and is adopted in current road construction and rehabilitation projects in Grenada (MOT, 2018, 2019). In this functional classification system, Grenada’s roads are categorized as expressways (Class 1A-Regional road), arterials (Class 1B-Regional road), collectors/district/secondary roads (Class 2-District road), and local/tertiary roads (Class 3-Local road). Class 4-Access road are private roads and lanes (public or private) which are not considered in this study, since many are unpaved, not developed or maintained by the government, or challenging to estimate accurately.

To quantify and map the in-use road material stocks in Grenada, road network GIS data from CHARIM were used to classify the road network, calculate the road surface area, estimate the road material stocks, and map the spatial distribution of stocks. The functional classification of the road network was achieved based on a semi-automated GIS approach developed for this study, especially since Grenada has many road segments that would be challenging to identify manually. The classification system is shown in Figure 2.4. Road network data from CHARIM had an initial road classification that can be used as the first criterion in the classification system. The three initial road classes included “main roads” (primary roads including expressways and arterials), “roads” (including paved secondary and tertiary roads), and “unpaved roads”. Since there was only one expressway (i.e., Maurice Bishop Memorial Highway) in Grenada, the Class 1A-Regional road was identified manually. Other “main roads” were assigned to Class 1B-Regional road. “Unpaved roads” were categorized into Class 3-Local road which have high accessibility and low mobility. Generally, secondary roads/collectors should provide connections between primary roads and tertiary roads/local roads, while tertiary roads/local roads can connect to any type of roads (U.S. Department of Transportation Federal Highway Administration, 2013). Therefore, the spatial relationship between “roads” and “main roads” (primary roads) was checked. “Roads” that were not connected to primary roads were assigned to Class 3-Local road. In addition, secondary roads/collectors tend to have longer served distances and road lengths compared to tertiary roads/local roads (U.S. Department of Transportation Federal Highway Administration, 2013). Therefore, the remaining “roads” were further divided based on their locations (i.e., urban built-up areas or rural areas) and road lengths. If “roads” were longer than the threshold (200 m for urban built-up areas and 600 m for rural areas), they were assigned to Class 2-District road. Otherwise, they were assigned to Class 3-Local road. The threshold was determined through several trial runs and verified by the small-scale Grenada road map and road statistics report.

To ensure the feasibility of this approach, several tests were conducted, and the classification results were verified and edited through visual interpretation based on a composite of sources and information. This approach for verifying the road types included crosschecking satellite images from Google Earth Pro, road layers from OpenStreetMap and Google Map, the national road network map, and photos gathered from fieldwork or Google Street View.

2.2.1.1.2 Road classification based on road pavement

Roads in the same functional road class can have several types of pavement structures and different pavement structures can result in different material intensities. Therefore, the second step in road classification was to further classify functional road classes into different road types based on pavement structures. The American Association of State Highway and Transportation Officials (AASHTO) guide for pavement design is one of the popular road design standards used in North America and is adopted by MOT for the current road design in Grenada (MOT, 2018, 2019). According to AASHTO pavement design guide and MOT road design report (MOT, 2018, 2019; U.S. Department of Transportation Federal Highway Administration, 2017a), the pavement structure consists of subbase, base course, and surface course and is placed on the natural subgrade/roadbed (as shown in Figure 2.5).

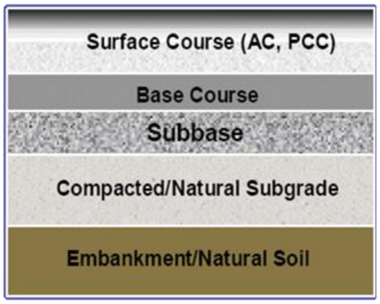

Figure 2.5: *Components of the pavement structure (U.S. Department of Transportation Federal Highway Administration, 2017a).*

Based on different pavement structures, roads in Grenada were classified into three classes, (a) rigid concrete pavement, (b) flexible asphalt pavement, and (c) unpaved roads. The description of different pavement types is summarized in Table 2.1. The material of the road surface layer (i.e., the "surface material") was the criterion used for identifying different pavement types. In the road classification system (shown in Figure 2.4), Class 1A/B-Regional roads were all paved with asphalt concrete. Class 2-District roads were further divided into Class 2A-District roads (flexible asphalt pavement) and Class 2B-District roads (rigid concrete pavement). Class 3-Local roads were divided into Class 3A-Local roads (flexible asphalt pavement), Class 3B-Local roads (rigid concrete pavement), and Class 3C-Local roads (unpaved). Due to the limitation of available data and travel restrictions for conducting fieldwork, the classification was conducted through manual interpretation of various sources of information. This included available fieldwork photos, remote sensing images, Google Street View, Google Earth Image, information in OSM layers, and previous Grenada road project reports (MOT, 2018, 2019).

Table 2.1: *Road classification by pavement type (derived from U.S. Department of Transportation Federal Highway Administration, 2017a).*

Pavement type	**Description**	**Materials**	**Possible road types in Grenada**
Flexible asphalt pavement	• Roads with asphalt concrete (AC) surface layer. The surface layer can be divided into seal coat, surface course (wearing layer) and binder course (hot mix asphalt layer). • Flexible asphalt pavements are flexible and will deform under high pressure. • Due to the flexible nature, flexible asphalt pavements can better accommodate the ground movement. • Flexible asphalt pavements are easy to repair.	• Aggregates (may include sand) • Asphalt concrete (mixture of asphalt and aggregates, excluding roadbed)	• Class 1A-Regional road (Expressway) • Class 1B-Regional road • Class 2A-District road (flexible asphalt pavement) • Class 3A-Local road (flexible asphalt pavement)
Rigid concrete pavement	• Roads with Portland cement concrete (PCC) surface layer. • Rigid concrete pavements have a high flexural strength and will not bend under pressure. • Rigid concrete pavements are not flexible so they will crack if the ground shifts or settles. • Rigid concrete pavements are durable and last longer than other pavement types.	• Aggregates (may include sand) • Cement concrete (mixture of cement and aggregates, excluding roadbed)	• Class 2B-District road (rigid concrete pavement) • Class 3B-Local road (rigid concrete pavement)
Unpaved road	• Roads are not paved but graded and drained. The surface layer has a mix of soil, gravel, crushed stone, etc.	• Aggregates (may include sand)	• Class 3C-Local road (unpaved)

*Asphalt concrete is commonly called asphalt. Cement concrete is commonly called concrete. Asphalt and concrete are two common composite materials used to surface roads.

2.2.1.2 Physical size of road

The physical size of roads and calculating surface area involves considering two measurements of, (a) road width, and (b) road length. Since the accurate width of each road segment in the road network of Grenada is not publicly available, an estimated width was assigned for each road type in the classification system (refer to the road cross-section profiles in

Figure 2.5). The estimated width was determined based on previous road project reports in Grenada (MOT, 2018, 2019), which provide typical road cross-section drawings and geometric design of existing and planning roads. The length of roads was measured physically based on GIS datasets. The total surface area of roads was then calculated by multiplying the length by the width.

2.2.1.3 Material intensity (MI)

In bottom-up material stock analysis, each road type is assumed to share the same pavement structure and have the same material intensity. Since a standard road pavement design for Grenada was not available, the typical pavement structures of roads were derived from previous road project reports and design manuals from MOT (MOT, 2018, 2019). As previously discussed, the pavement structure consists of three pavement layers (i.e., subbase, base, and surface layers), and each pavement layer is composed of one main type of material (e.g., aggregate, asphalt concrete, cement concrete). The typical road cross-section profiles for each road type pavement structure are illustrated in Figure 2.6, which shows the road width, the thickness of each layer, and the materials that compose the paving layer. The material intensity (kg/m^2) of material *i* in road type *x* was then estimated by Equation 1 below:

$$MI_{i,x} = D_i \times THK_i \tag{1}$$

where $MI_{i,x}$ is the material intensity of material *i* in road type *x*; D_i is the standard material density (kg/m^3) of material i (refer to Table 2.2); THK_i is the total thickness (m) of the layers composed of material *i*. A set of material intensity typologies were then developed for roads in Grenada and is summarized in Table 2.3.

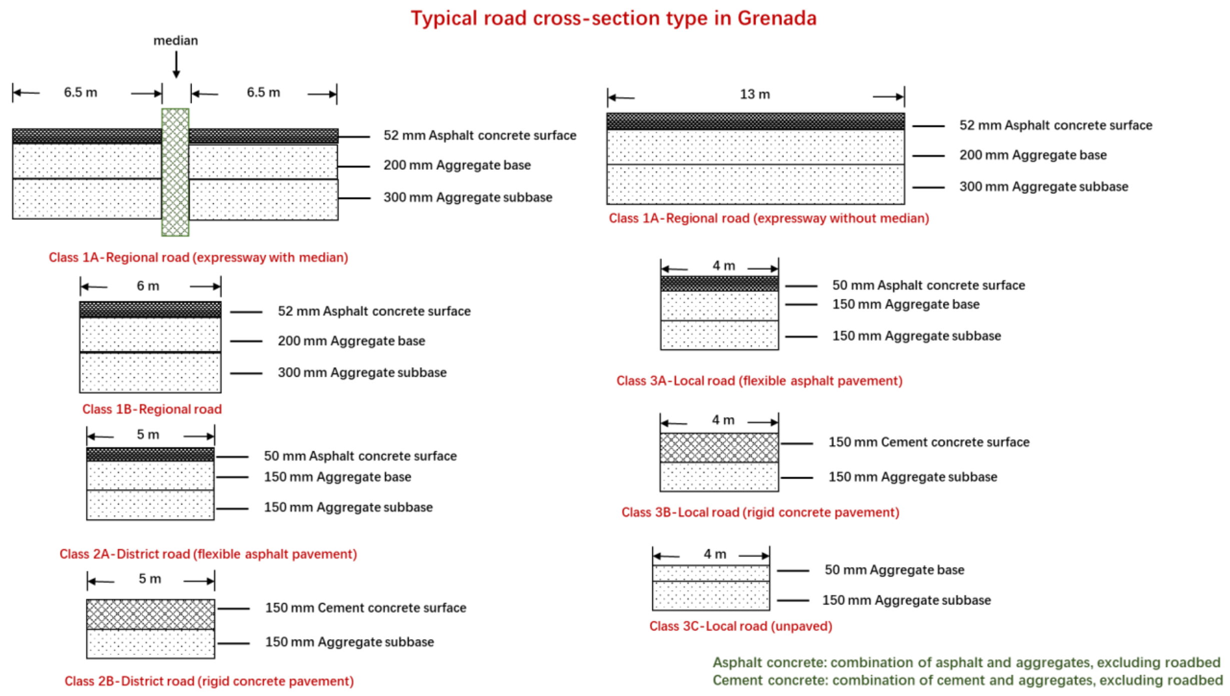

Figure 2.6: *Typical road cross sections in Grenada used for developing material intensity.*

Table 2.2: *Standard material density values for materials used for estimating material intensity.*

Materials	**Density value**	**Source**
Asphalt concrete	2,322 kg/m^3	https://www.gigacalculator.com/calculators/asphalt-calculator.php
Cement concrete	2,130 kg/m^3	
Aggregate	1,680 kg/m^3	

Table 2.3: *Material intensity typology break down of materials. Units:* kg/m^2.

Road type	**Material intensity (kg/m^2)**		
	Aggregate	**Concrete**	**Asphalt**
Class 1A-Regional road (expressway with median)			
Surface			120.744
Base	336		
Subbase	504		
Total	***840***	***0***	***120.744***
Class 1A-Regional road (expressway without median)			
Surface			120.744
Base	336		
Subbase	504		
Total	***840***	***0***	***120.744***
Class 1B-Regional road			
Surface			120.744
Base	336		
Subbase	504		
Total	***840***	***0***	***120.744***
Class 2A-District road (flexible asphalt pavement)			
Surface			116.1
Base	252		
Subbase	252		
Total	***504***	***0***	***116.1***

Class 2B-District road (rigid concrete pavement)			
Surface		319.5	
Base			
Subbase	252		
Total	***252***	***319.5***	***0***
Class 3A-Local road (flexible asphalt pavement)			
Surface			116.1
Base	252		
Subbase	252		
Total	***504***	***0***	***116.1***
Class 3B-Local road (rigid concrete pavement)			
Surface		319.5	
Base			
Subbase	252		
Total	***252***	***319.5***	***0***
Class 3C-Local road (unpaved)			
Surface			
Base	84		
Subbase	252		
Total	***336***	***0***	***0***

2.2.1.4 Road stock estimation

With the area of roads and material intensities established, the materials stocked in roads are calculated by Equation 2:

$$MS_i = \sum_x A_x \times MI_{i,x} \tag{2}$$

where MS_i is the total road stock of material i; A_x is the total surface area of road type *x*; $MI_{i,x}$ is the material intensity (kg/m^2) of material *i* in road type *x* (Nguyen et al., 2019). Finally, total surface area of road type *x* (A_x) are calculated by Equation 3:

$$A_x = Total\ Length_x \times Road\ Width_x \tag{3}$$

2.2.2 Impacts of including road stocks on total material stock estimation

Previous research for Grenada only considered building stocks in the total material stock estimation (De Kroon, 2020; Symmes et al., 2019). The total amount of road stocks on Grenada was compared with the total building stocks previously estimated by De Kroon (2020). The percentage of road stocks of the total stock account was calculated, and the processed road stock dataset was added to the geodatabase for Grenada, which can be utilized for future studies.

2.2.3 Linking building services to roads

Roads provide access to different services and facilitate the circulation of people, goods, and materials. Each road in the Grenada geodatabase was linked to the provision of services by identifying associated buildings. This provides insight into which services are facilitated by each road segment and how road stocks are associated with different services. Building service categories in Grenada were derived from previous research (De Kroon, 2020) and adopted for this study (Table 2.4).

Table 2.4: *Building service categories in Grenada.*

Building service category	
Health	Commercial
Tourism	Industrial
Residential/Shelter	Institutional - Education
Cultural	Institutional - Other
Recreational	Agriculture
Transportation	Mixed Use (commercial & residential)

The percentages of different services associated with each road segment were calculated using a “buffer” approach. A buffer polygon was developed around each road segment to a specified distance and the numbers of buildings with different services within the buffer were identified and counted. The percentage of different services associated with each road segment was then calculated by Equation 4 below:

$$Percentage\ of\ service\ i = \frac{the\ number\ of\ buildings\ with\ service\ i\ within\ the\ buffer}{total\ number\ of\ buildings\ within\ the\ buffer} \qquad (4)$$

Different buffer distances were adopted for each road type, since the minimum building set back (i.e., the minimum distance between the road central line and the building lines or eaves) of each road type is different. Higher-level roads are intended to provide traffic movement instead of property access and are therefore further away from buildings. Lower-level roads have higher accessibility and are closer to buildings. Buildings sited on either side of the road were considered to be associated with the road and should be within or intersecting the buffers. Therefore, buffer distances were derived from the sum of the minimum building set back distance (derived from MOT (2018)) and the average side length of buildings (measured based on GIS datasets). Several tests were run to verify and adjust the buffer distances and the final buffer distances of different road types are shown in Table 2.5.

Table 2.5: *Distances of buffers for different road types.*

Road type	Buffer distance (m)
Class 1A-Regional road (expressway with median) Class 1A-Regional road (expressway without median)	30
Class 1B-Regional road	20
Class 2A-District road (flexible asphalt pavement) Class 2B-District road (rigid concrete pavement)	15
Class 3C-Local road (flexible asphalt pavement) Class 3B-Local road (rigid concrete pavement) Class 3C-Local road (unpaved)	10

*The buffer distance was measured from the central line of the road to the buffer edge.

With the percentage of different services associated with each road segment, the amount of road stocks associated with different services could be calculated and the total amount of road stocks of different services could be estimated.

2.2.4 Identifying road stocks vulnerable to sea level rise

Roads that are situated along coastal areas are particularly vulnerable to sea level rise (SLR) caused by climate change. Identifying road stocks and associated services that would be exposed to future SLR scenarios could be vital for future sustainable development. According to the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), by the end of this century, global mean sea level (GMSL) will rise between 0.29 m (under RCP 2.6, low emission scenario) and 1.1 m (under RCP 8.5, high emission scenario) (IPCC, 2019). Some researchers point out that the model used in SROCC may underestimate the likely upper level (1.1 m) of sea level projections (Grinsted & Christensen, 2021). Bamber, Oppenheimer, Kopp, Aspinall, and Cooke (2019) state that the sea level rise in excess of 2.0 m may happen by 2100. Based on the ranges suggested from these reports and journal articles, five SLR scenarios were considered in this study: 0.25 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m (by 2100).

The Digital Elevation Model (DEM) data (2016) for Grenada are not suitable for modelling small incremental changes in SLR due to its low resolution (5 m pixel size) and unknown elevation accuracy. A new LiDAR data collected by Land Use Division, Ministry of Agriculture, Government of Grenada in 2017 has a finer resolution (3-5 cm pixel size) and higher elevation accuracy (< 10 cm) and was used to generate a Digital Terrain Model (DTM) and to derive inundation zones. A DTM represents a continuous terrain surface without any ground cover and structures (i.e., the bare ground surface; Hirt, 2014; Li, Zhu, & Gold, 2004). DTMs generated from LiDAR point clouds can accurately represent geomorphometric characteristics of the surface and have been widely applied to resource and hazard assessment, engineering structure planning, coastal protection (e.g., beach erosion or inundation analysis), and hydrology (Amoura & Dahmani, 2022; Castañeda & Gracia, 2017; Hirt, 2014; Vernimmen et al., 2019). Raw LiDAR points cloud can be classified as non-ground (e.g., buildings, trees, and shrubs) and ground points. Ground points can be converted into a DTM, while all points (ground and non-ground points) can be converted into a Digital Surface Model (DSM)[2]. "DEM" is often considered as a general term for "DTM", "DSM", and any other elevation models but sometimes used synonymously with "DTM" or "DSM" (Z. Chen, Gao, & Devereux, 2017; Hirt, 2014; Podobnikar & Gadal, 2009). Guth et al. (2021) and Z. Chen et al. (2017) recommended to treat "DEM" as a general term and use the term "DTM" for the bare terrain surface generated from ground points since "DSM" has been widely used in current LiDAR studies. In this study, a DTM generated from LiDAR ground points was used to represent bare terrain and assess the

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[2] Digital Surface Model (DSM) represents Earth's surface including all features on it (Z. Chen et al., 2017).

coastal vulnerability to sea level rise since the DTM had a high resolution (50 cm × 50 cm) and could better approximate the coastal terrain.

Due to the limited computer processing power and the long data processing time, a sample test site of four tiles of LiDAR data were selected covering about 3.87 km^2. This sample site is situated in St. George's and covers the upper part of Martins Bay and St. George's Harbour (as shown in Figure 2.7). Large numbers of buildings and roads are located in vulnerable low-lying coastal areas. The sample site is used as a proof of concept to demonstrate the methodology developed in this study and modelling effects of SLR on materials stocks for a highly populated area of Grenada.

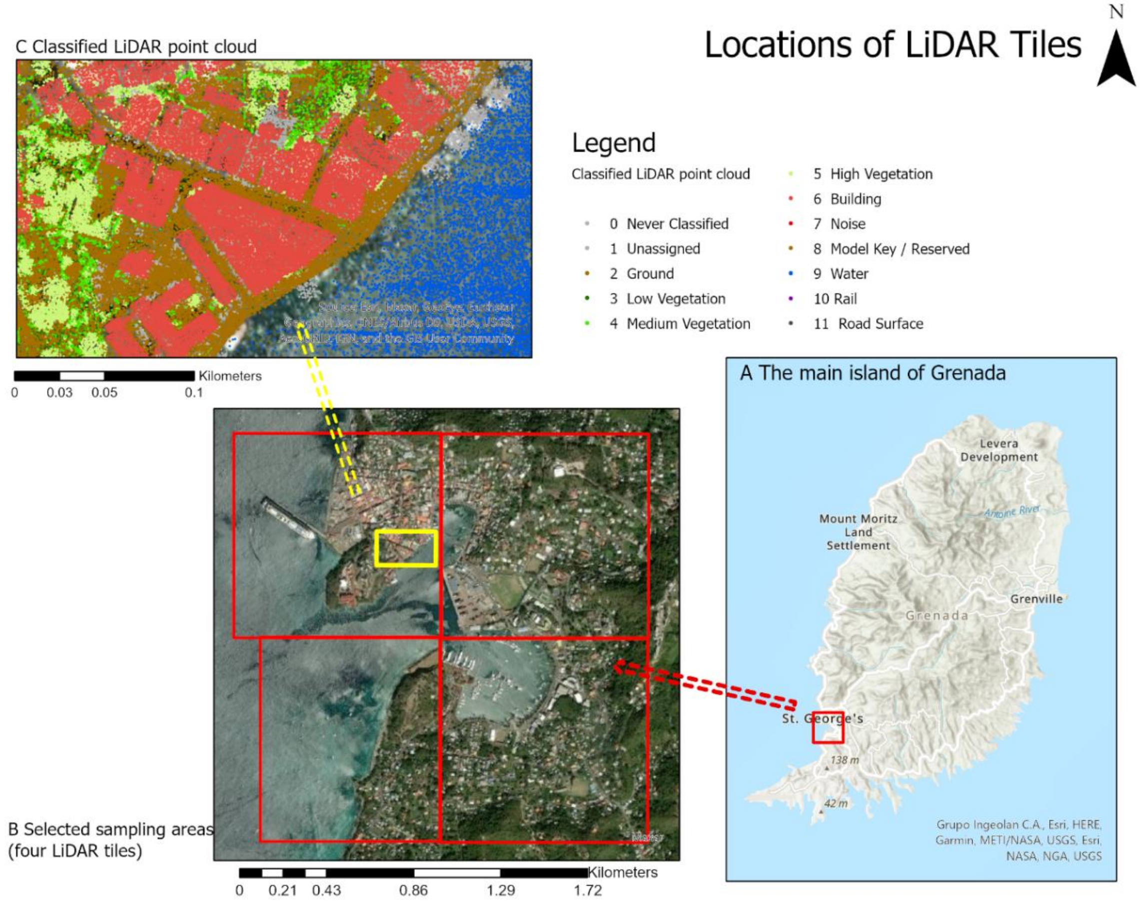


Figure 2.7: Locations of four LiDAR tiles covering a sample test site in St. George's.

The procedure of analyzing potential road stock lost due to SLR followed six major steps: (1) the shoreline was extracted from the classified LiDAR ground points and edited manually through visual inspection; (2) the mean sea level (0.5 m) was derived from the mean elevation of classified water points near the shoreline; (3) a DTM was generated from classified ground points; (4) inundation zones were derived from the DTM by setting the elevation value to 0.75 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m (mean sea level 0.5 m + sea level rise scenarios); (5) zones that were isolated or not hydrologically connected with the sea were deleted (following the "bathtub" approach; Gesch, 2009); and (6) inundation zones were overlaid with the road network data to calculate the exposure of road stocks and related services in different SLR scenarios. The LiDAR processing was conducted using the Whitebox Geospatial Analysis Tools, a cross-platform and open-source geospatial data analysis software package. Other analytical operations were performed using ArcGIS and ArcGIS Pro.

2.3 Results

The following sections describe the results of this study. The classified road network in Grenada is shown in Section 2.3.1. Section 2.3.2 reports the quantity of materials stocked within the road network, while Section 2.3.3 assesses the magnitude of change in total material stock estimation after including road stocks. Spatial distributions of road stocks are then mapped using GIS techniques in Section 2.3.4. Sections 2.3.5 and 2.3.6 examine road stocks in terms of their relationship with building services and evaluate how the road stocks and associated services may be affected under future sea level rise scenarios.

2.3.1 The road network in Grenada

The spatial distribution of the road network in Grenada is illustrated in Figure 2.8, showing the basic road hierarchy in Grenada, which comprises of Class 1A-Regional roads (expressway), Class 1B-Regional roads, Class 2-District roads, and Class 3-Local roads. Note that Grenada has only one expressway called the Maurice Bishop Memorial Highway, which connects to the Maurice Bishop International Airport in the southwest of the island. Class 1B-Regional roads (in red) are the primary arterials connecting major cities or towns, airports, and ports along the coast. The total length of paved and unpaved roads in Grenada was 1,594.52 km according to the GIS data in 2015. Class 3-Local roads contributed to the largest proportion (about 57%) of the Grenada road network with a total length of 916.03 km.

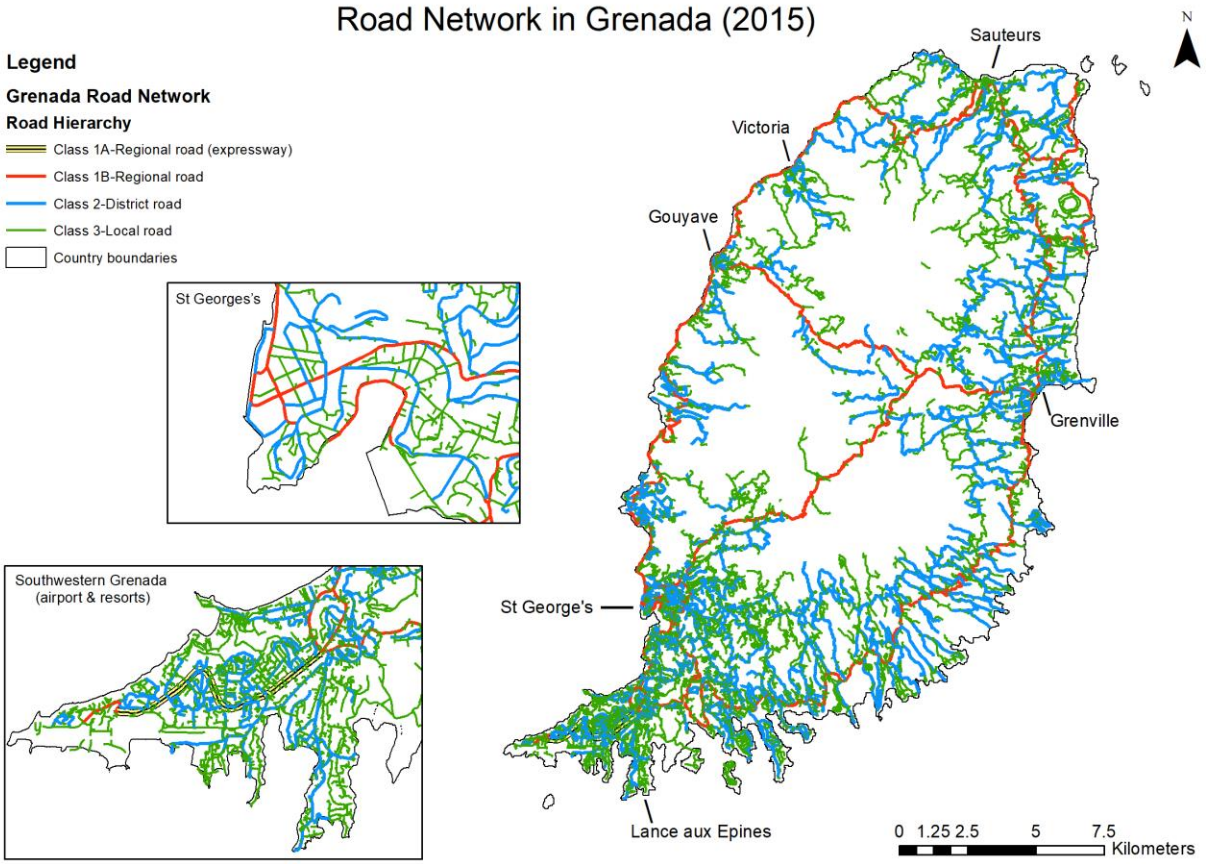


Figure 2.8: *Road hierarchy in Grenada.*

Figure 2.9 shows the road classification in Grenada in which roads are categorized by their surface pavement types (e.g., flexible asphalt pavement, rigid concrete pavement, unpaved). In Grenada, 87% of roads were paved in 2015. Rigid concrete roads were most common (61% of roads) followed by flexible asphalt roads (26%) and unpaved roads (13%). Class 1-Regional roads were all paved with asphalt concrete.

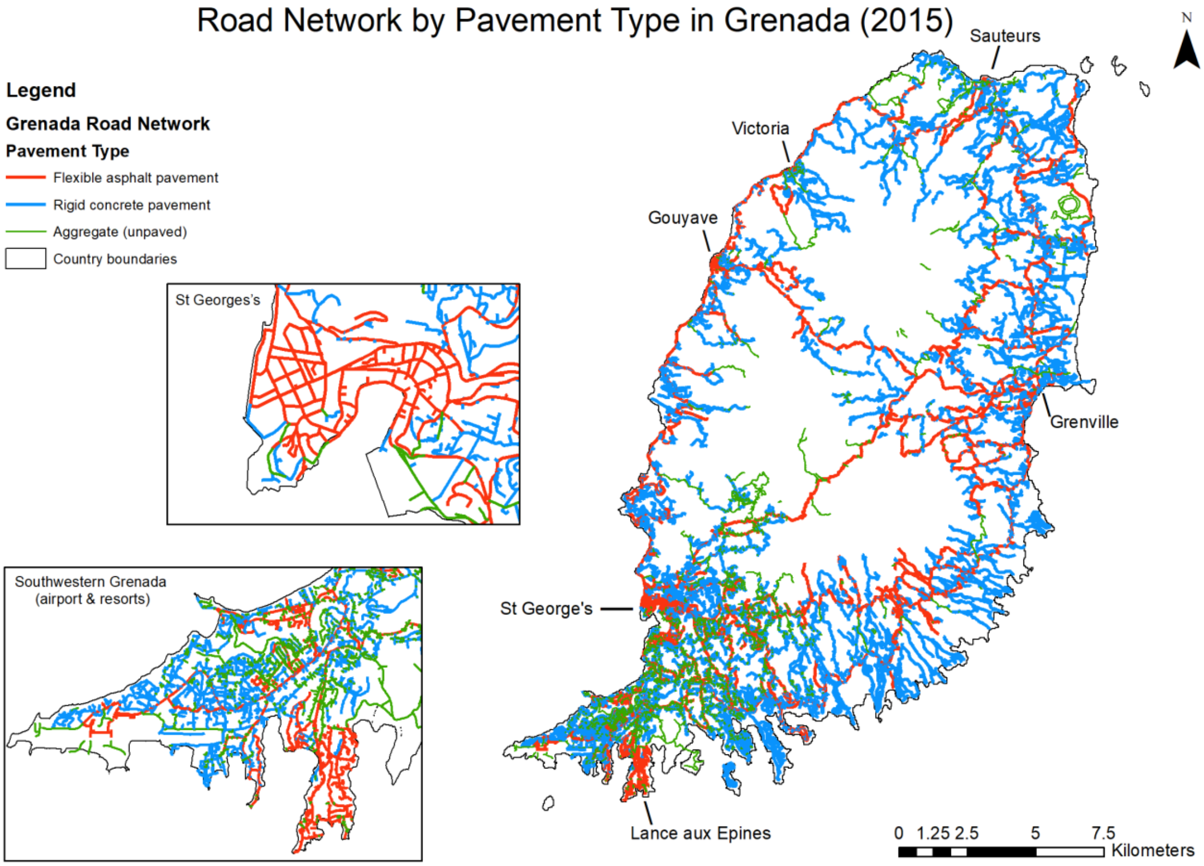


Figure 2.9: *Road network by pavement type in Grenada.*

2.3.2 Material stocks within the road network

The total amount of material stocks within Grenada's road network was about 4,375 kilo tonnes in 2015, equaling to 40.96 tonnes per capita. Table 2.6 and Figure 2.10 present the volume and percentage of road stocks according to different types of materials (e.g., asphalt concrete, cement concrete, aggregate). Since every road type uses aggregates to build its base and subbase layers, aggregate stocks account for the largest proportion of road stocks (2,757.67 kilo tonnes, about 63%) followed by cement concrete (31%) and asphalt concrete (6%).

Table 2.6: *Road material stocks by material category in Grenada.*

Material category in road stocks	Material stocks (tonne)	Material stocks (kilo tonne)	Material stocks per Capita (t/capita, 2015)
Asphalt concrete	255,788.57	255.79	2.39
Cement concrete	1,361,655.84	1,361.66	12.75
Aggregate	2,757,673.12	2,757.67	25.81
Total	4,375,117.54	4,375.12	40.96

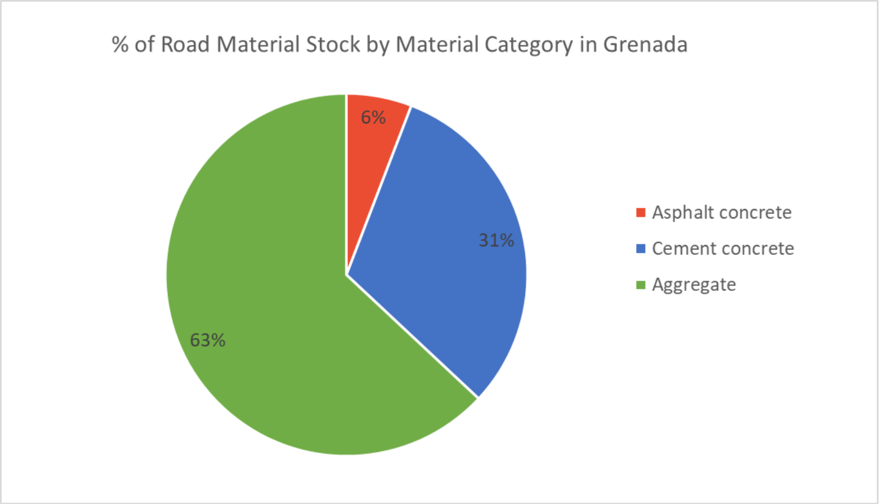


Figure 2.10: *% of road material stock by material category in Grenada.*

2.3.3 Road material stocks in total material stock account

Since previous material stock accounting for Grenada only considered building stocks (De Kroon, 2020; Symmes et al., 2019), it is important to assess the magnitude of change after including road stocks in the material stock account. The amount of estimated road stocks was compared with total material stocks (i.e., only building stocks) computed from a previous study by De Kroon (2020). As shown in Table 2.7, the ratio of total road stocks to total building stocks is about 1:3 and road stocks accounted for about 24% of the total material stocks. This supports the hypothesis that road stocks account for a large share of total material stocks in Grenada and should therefore not be omitted. Including road stocks in the total material stock estimation resulted in a total material stock output of 18,387.40 kilo tonnes (172.13 t/capita), increasing by 31% compared to the total material stock amount previously computed by De Kroon (2020).

Table 2.7: *Road stocks compared with building stocks.*

	Asphalt concrete	**Cement concrete**	**Aggregate**	**Steel**	**Timber**	**Total**	**Total MS (building + road stocks) (kilo tonne)**
Building material stocks (kilo tonne)	/	10,887.83	2,253.37	213.73	657.35	14,012.28	18,387.40
Road material stocks (kilo tonne)	255.79	1,361.66	2,757.67	/	/	4,375.12	
Road MS/Building MS	/	0.13	1.22	/	/	0.31	/
Road MS/Total MS	/	0.11	0.55	/	/	/	0.24

2.3.4 Spatial distributions of road stocks

Three maps (Figure 2.11, 2.12, & 2.13) illustrate the spatial distribution of road stocks on the main island of Grenada. Figure 2.11 shows the road stock distribution by parish. The largest proportion of the road stocks are located in St. George parish (the southwestern part of the island), which is where most commercial activities occur, as well as where many tourist resorts are located and much of the population resides. St. Andrew parish, the largest parish of Grenada in terms of area, contains the second largest proportion of road stocks.

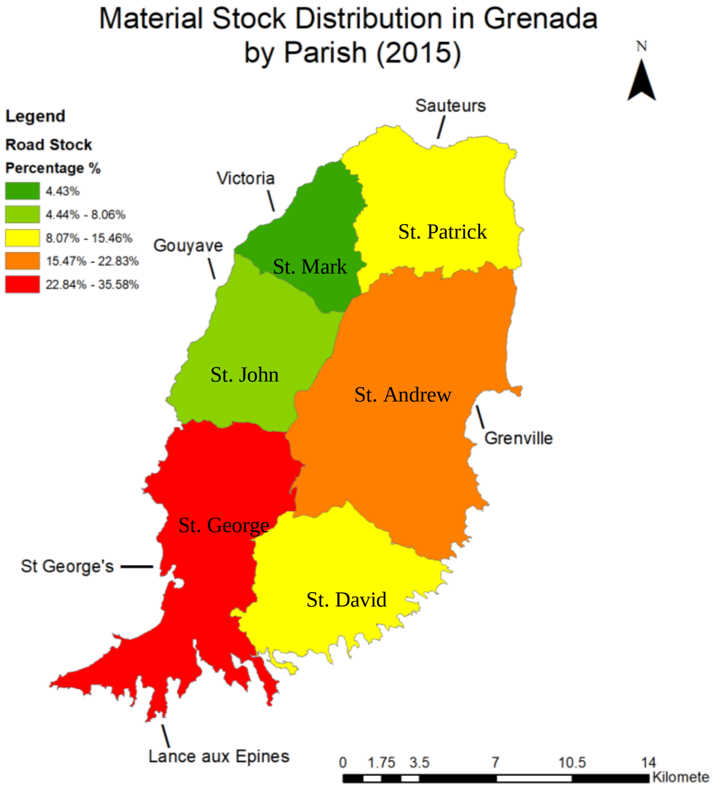


Figure 2.11: *Road material stock distribution by parish in Grenada (2015).*

Figure 2.12 presents the building and road stock density (MS amount/area) by Census Enumeration District (ED) in Grenada. ED is the smallest spatial unit of Grenada census data.

Calculating and visualizing material stocks at the ED level enable comparison of material stock data with census statistics about the population in Grenada (Symmes et al., 2019). The map in Figure 2.12 illustrates that both building and road stocks are heavily concentrated and accumulated in major cities/towns and along coastal areas. A large proportion of both building and road stocks are located in the southwestern corner of the island, where the airport and main tourist resorts are situated. St. George’s, the capital city of Grenada, contains a high concentration of stocks, since this is where a high intensity of infrastructure is located. A second cluster of stocks is located on the east coast, where the second-largest urban centre, Grenville is located. Compared with the building stocks, road stocks tend to be more distributed throughout the island connecting areas of development and the observed differences between EDs are smaller.

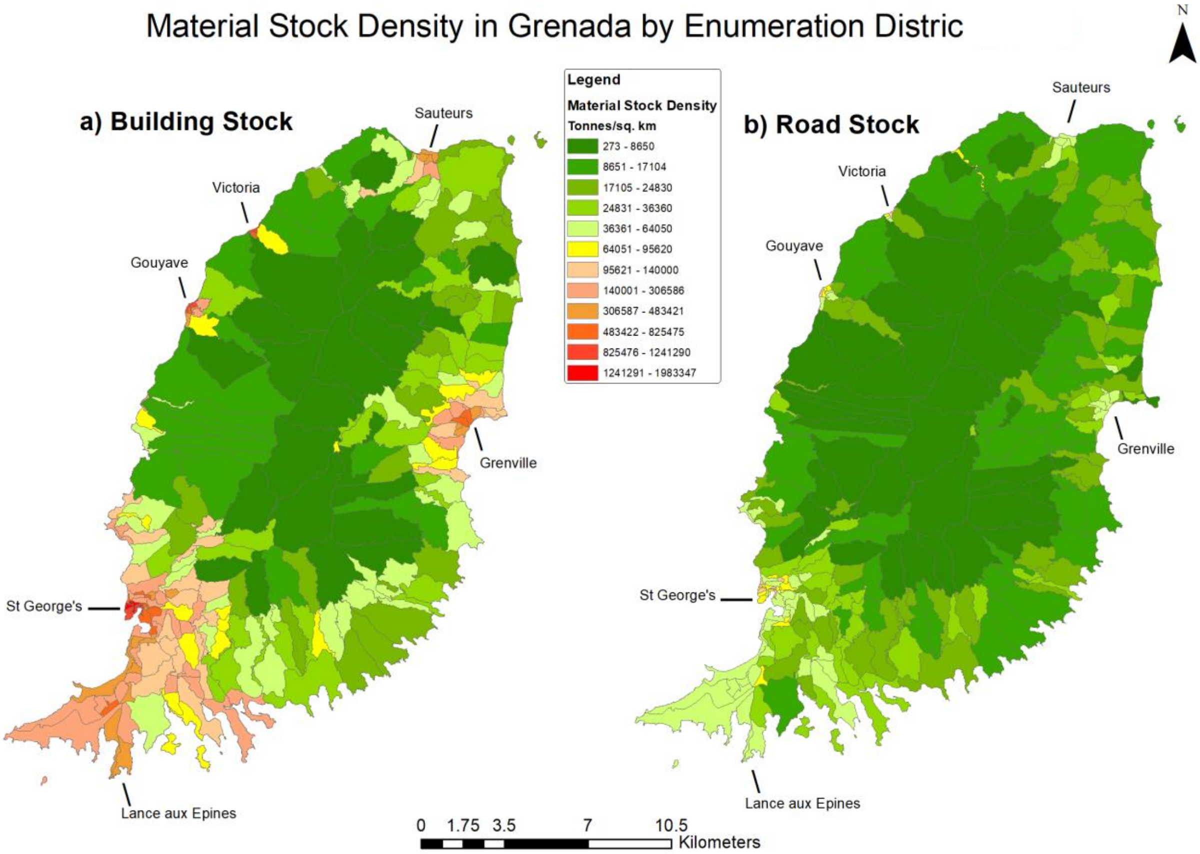


Figure 2.12: *Material stock (road and building stock) distribution by Enumeration District (ED) in Grenada.*

The material stock distribution in Grenada is shown in a different way in Figure 2.13, where the building and road material stock density is displayed using a grid of 0.5 sq. km hexagons. In GIS analysis, hexagons have been useful for normalizing geography for mapping and may mitigate the effects caused by the massive disparity in some irregularly shaped polygons (e.g., census districts, county boundaries, etc.; ESRI, 2021a). With low perimeter-to-area ratio, hexagons can reduce sampling bias caused by edge effects of fishnet/square grids. Furthermore, the circularity of hexagons enables the representation of curves and connecting paths. Compared to fishnet grids which draw readers’ eyes to straight and parallel lines, hexagons can break up the line, reduce perceptual bias, and show the curves more naturally and clearly, which can better display stocks accumulated in curving road paths (Birch, Oom, & Beecham, 2007; ESRI, 2021a). The breakup of straight lines can also reveal some underlying patterns that may be inhibited in fishnet grids and better illustrate the spatial distribution of material stocks (Birch et al., 2007; ESRI, 2021a). Similar to what is found in Figure 2.12 (MS distribution by ED), this map illustrates the hotspots of building and road stocks in major cities/towns and along coastal areas. The roadways passing through interior mountainous regions are more prominent in the road stock hexagon map and are easier to visualize. Such roads connect the major towns on the island and such stocks contribute directly to supporting the flow of goods and services between urban areas and serve a critical function for the entire island, rather than just for local uses.

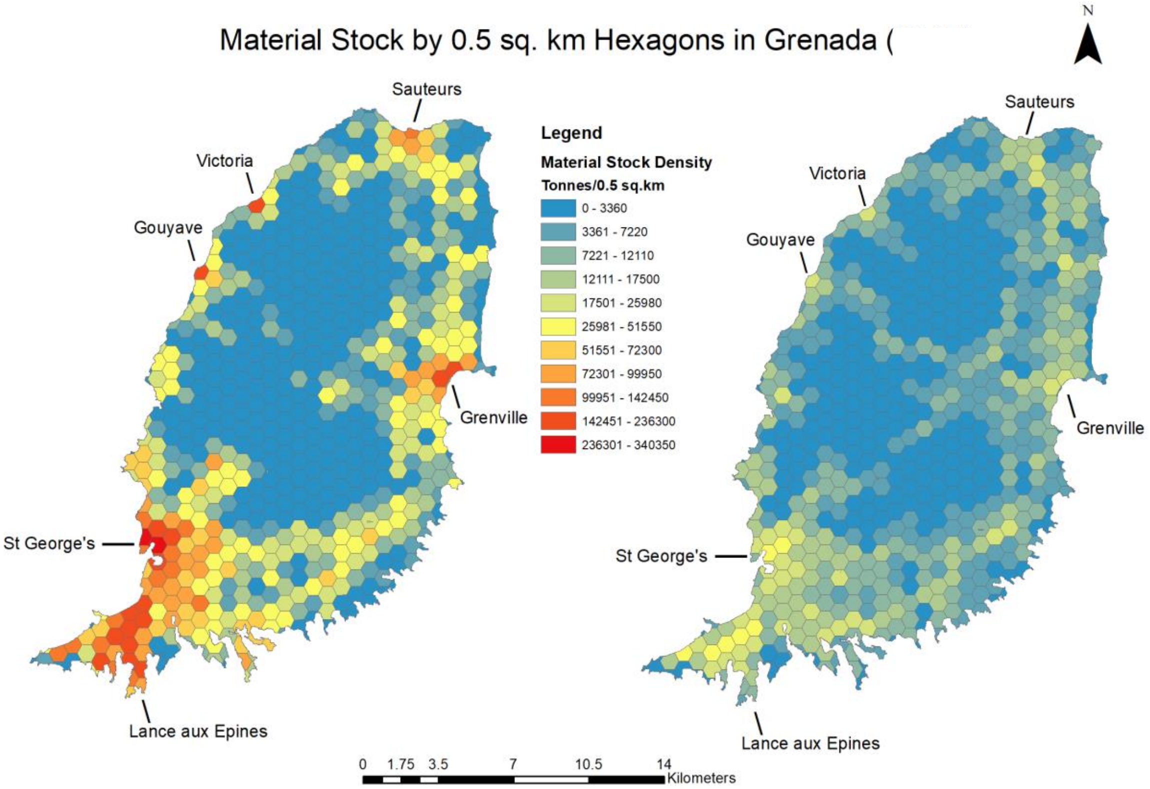


Figure 2.13: *Material stock (road and building stock) distribution by 0.5 sq. km hexagons in Grenada.*

Figure 2.14 shows the road stock density by different material categories at the ED level. It is visibly evident that aggregate stocks make up the largest proportion of road stocks compared to other types of materials. Both aggregate and concrete stocks have high densities along the coastline. Aggregate stocks have a similar spatial distribution pattern to building stocks (Figure 2.12). Asphalt stocks tend to cluster in urban centres, while concrete stocks tend to cluster in surrounding suburban residential areas and within tourism areas (e.g., southwestern corner of Grenada, near the airport and beaches).

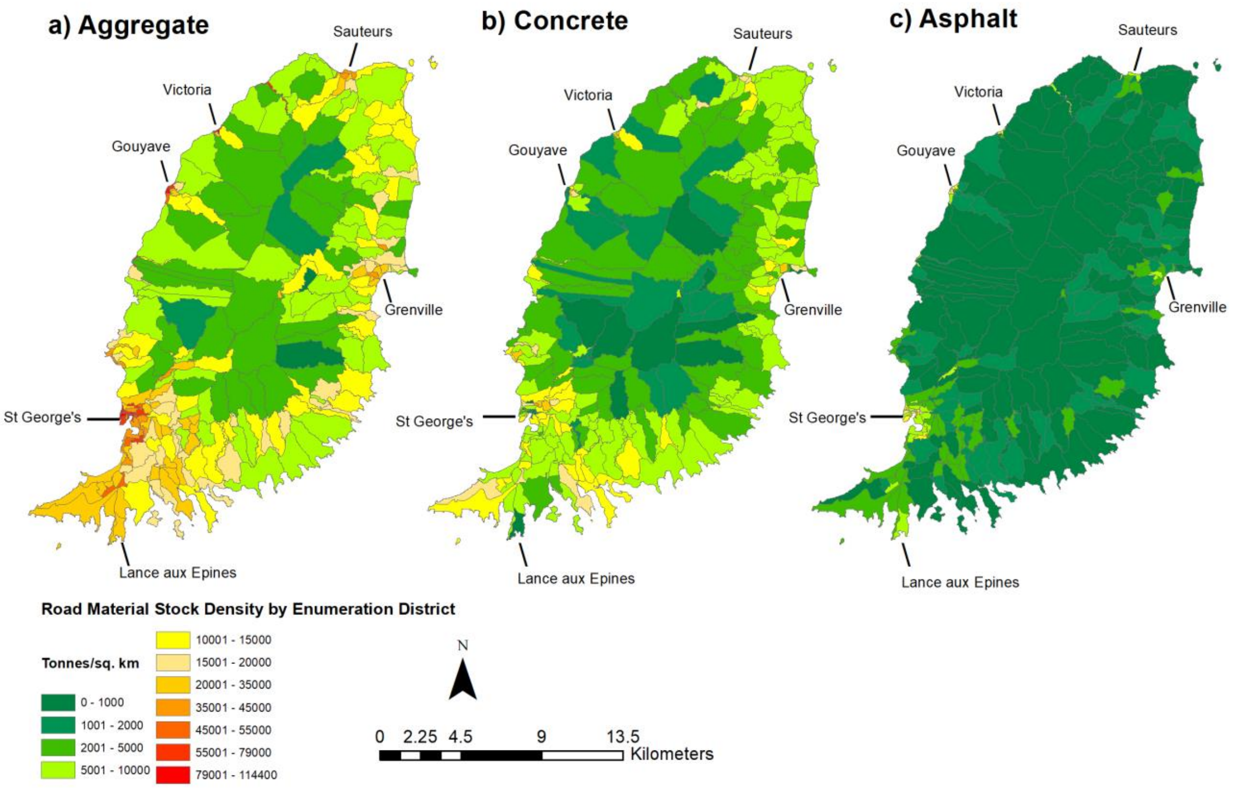


Figure 2.14: *Road material stock distribution (break down of three materials) by Enumeration District in Grenada (2015).*

2.3.5 Road stocks and associated services

The graph in Figure 2.15 illustrates the relationship between road stocks and the services provided by nearby buildings. It can be observed that the amount of residential stocks was 3,846 kilo tonnes (36 t/capita) accounting for 88% of total road stocks in Grenada, which was by far the majority. Tourism was the second-highest service category comprising 4% of total road stocks and followed by commercial (2.5%), mixed use (the mixture of residential and commercial services, 1.9%), and education (0.7%). Collectively, residential, tourism, and commercial services accounted for over 96% of total road stocks. Figure 2.16 visualizes the spatial distribution of road stocks associated with different service types. Road stocks related to residential sectors are distributed across the whole island, while stocks related to tourism are largely concentrated in enumeration districts located near beaches and close to the airport. Commercial, industrial, education stocks are located along the coastline and have a high accumulation in the southwestern area of the island, where the climate is favourable especially for tourism activities.

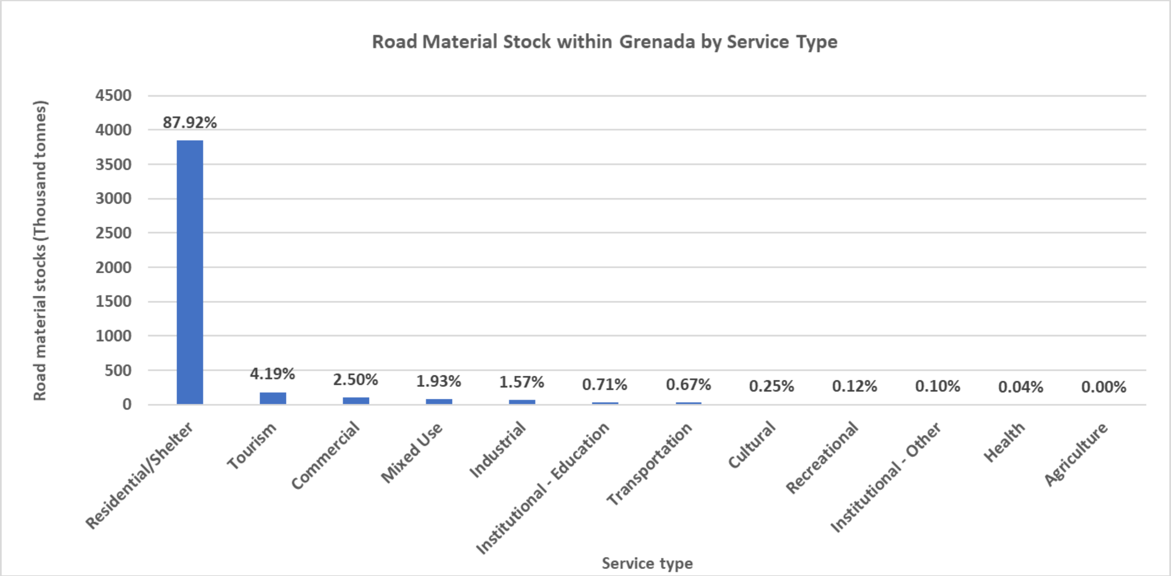


Figure 2.15: *Road material stock by service type in Grenada (2015).*

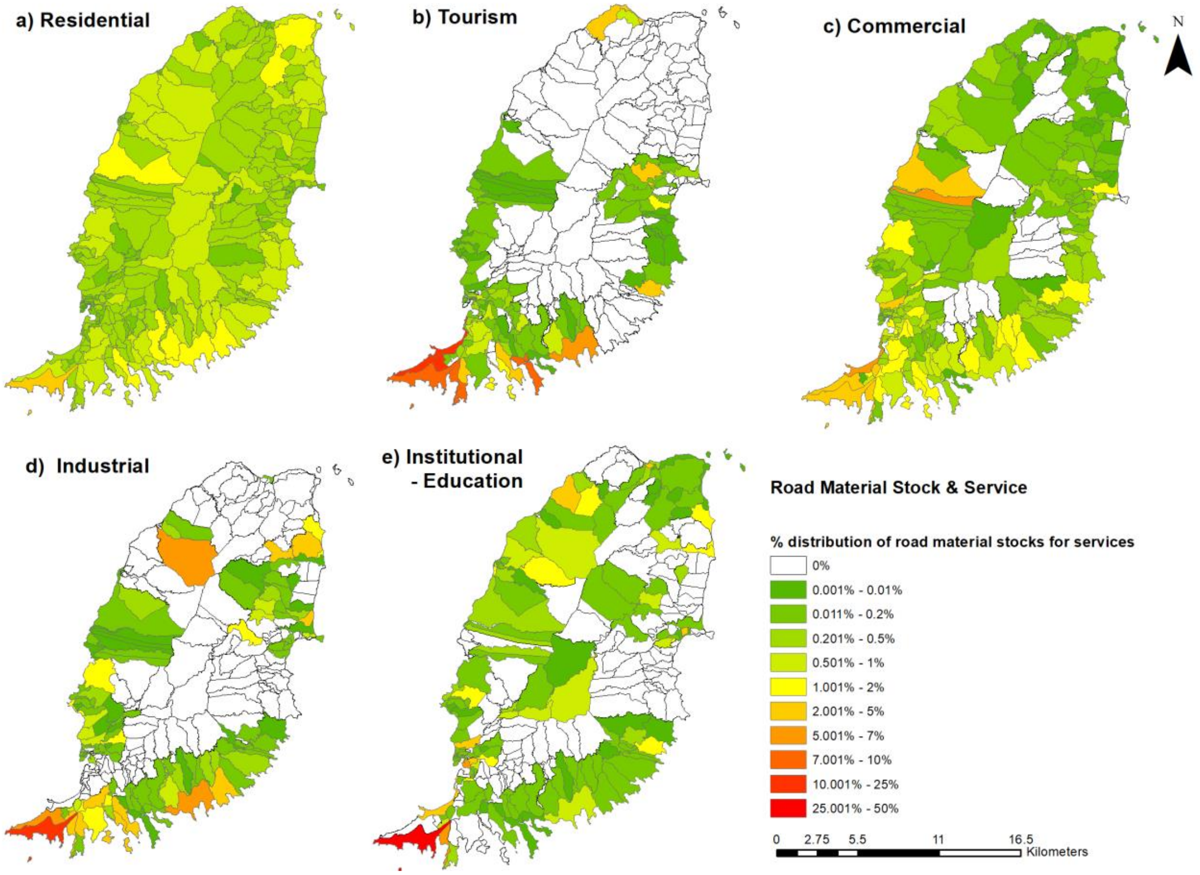


Figure 2.16: *Road material stock distribution and associated services by Enumeration District in Grenada (2015).*

2.3.6 Potential future loss of road stocks

To identify and assess roads stocks that are vulnerable to potential sea level rise in Grenada, five sea level rise scenarios were tested in a sample area in St. George's as previously explained in Section 2.2.4. Figures 2.17 and 2.18 highlight the roads that would be exposed under five sea level rise scenarios (0.25 m, 0.5 m, 1.0 m, 1.5 m, and 2.0 m). It is evident that the roads located near the shoreline of St. George's Harbor are highly vulnerable to future sea level rise. In the more conservative scenario of 0.25 m sea level rise, impacts are comparatively smaller along the shoreline and only a few road segments (highlighted in yellow) in the southern part of the harbour near the Port Louis Marina would be affected. When sea level rises to 0.5 m, the northern part of the harbour becomes significantly at risk, while a large part of Wharf Road located in the Carenage would be inundated. As sea level rise increases to 1.0 m, most of Wharf Road and Lagoon Road (highlighted in blue) would be affected, except for the middle part of the harbour, which is protected by a manmade platform (where the Grenada Port Authority is located) at a higher elevation. In the higher 1.5 m and 2.0 m sea level rise scenarios, the majority of roads along St. George's Harbor would be inundated, even including some inland roads such as those surrounding T.A. Marryshow Community College and the Tanteen Playing Field. The differences between all five scenarios are quite visually evident when mapped.

Table 2.8 summarizes statistics of vulnerable roads and their affected road stocks. Under the 2.0 m sea level rise scenario, over 5,220 meters of roads near the shoreline of St. George's Harbour would be exposed and about 18,187.52 tonnes of road stocks would be affected, which accounts for 1.16% of the road stocks in the Parish of St. George's. Among all the services, mixed use (combination of residential and commercial), commercial, and residential stocks are most vulnerable accounting for 36%, 31%, and 10% respectively, of total exposed stocks under the 2.0 m sea level rise scenario. Transportation also faces high risks since many ports or marinas are situated on the foreshore. Residential, mixed use, commercial, and transportation together occupy about 90% of total impacted stocks under all five sea level rise scenarios.

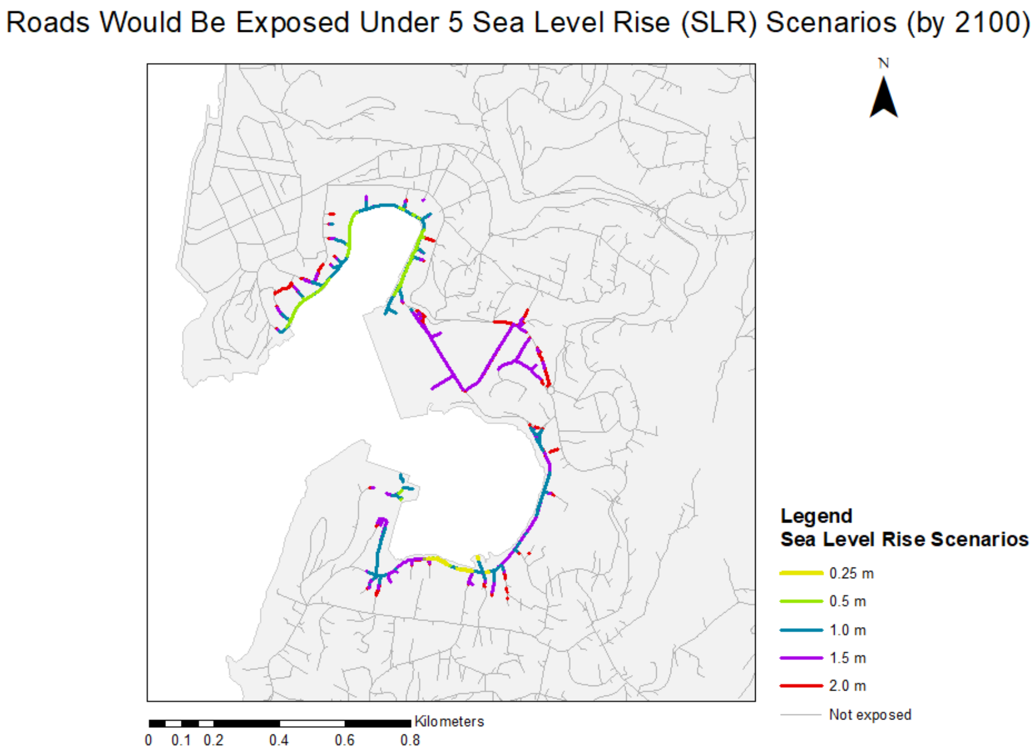


Figure 2.17: *Roads that would be exposed under five sea level rise scenarios (0.25 m, 0.5 m, 1.0 m, 1.5 m, and 2.0 m) by 2100.*

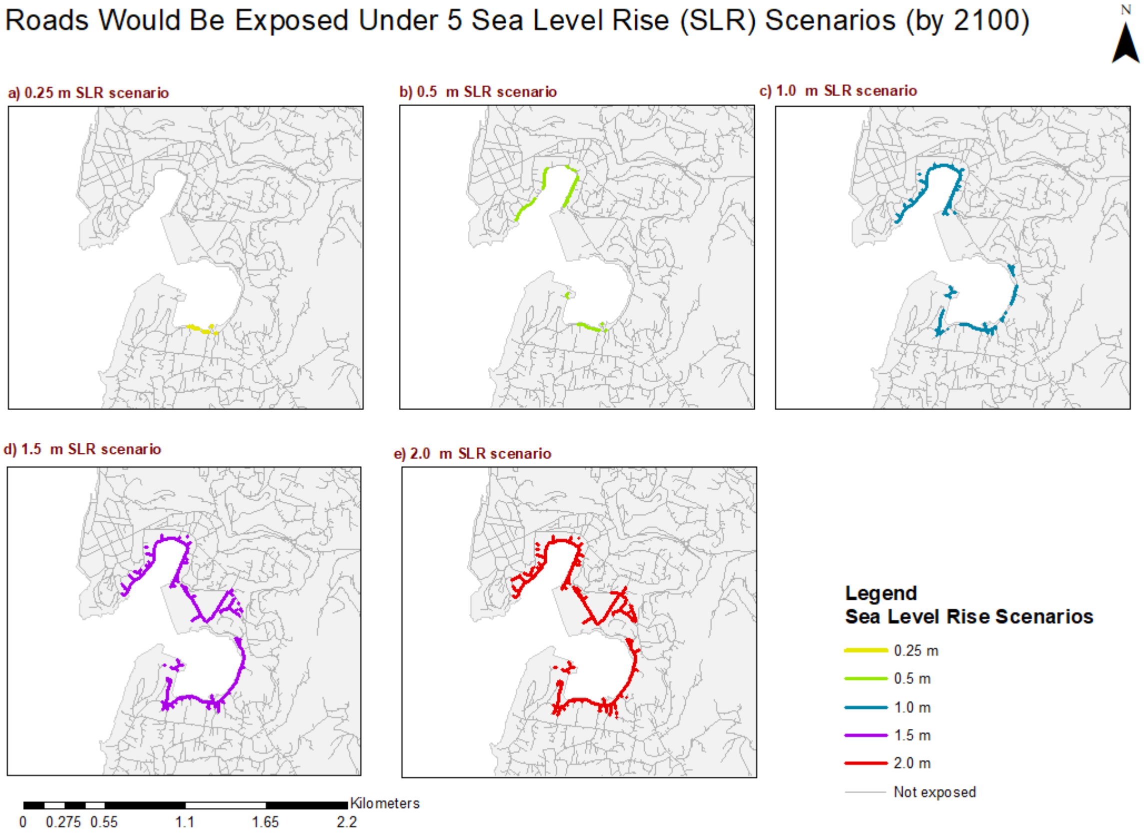


Figure 2.18: *Roads that would be exposed under five sea level rise scenarios (separate maps).*

Table 2.8: *The length of roads and the amount of road material stocks (by service type) that would be affected under five sea level rise scenarios.*

	Sea Level Rise Scenarios									
	0.25 m		0.5 m		1.0 m		1.5 m		2.0 m	
Affected length (m)	96.78		749.99		2,388.97		4,468.20		5,220.43	
Service type	MS exposed (t)	% of exposed MS	MS exposed (t)	% of exposed MS	MS exposed (t)	% of exposed MS	MS exposed (t)	% of exposed MS	MS exposed (t)	% of exposed MS
Tourism	27.49	5.18%	39.65	1.13%	137.58	1.36%	262.83	1.63%	284.93	1.57%
Residential/Shelter	420.50	79.27%	605.43	17.31%	2,451.59	24.21%	4,882.93	30.22%	5,562.25	30.58%
Cultural	7.50	1.41%	14.67	0.42%	61.22	0.60%	131.20	0.81%	151.41	0.83%
Recreational	0.00	0.00%	16.61	0.47%	21.93	0.22%	560.24	3.47%	629.95	3.46%
Transportation	2.50	0.47%	297.49	8.50%	1,177.85	11.63%	1,674.83	10.37%	1,752.13	9.63%
Commercial	69.96	13.19%	120.09	3.43%	1,022.06	10.09%	1,604.94	9.93%	1,835.80	10.09%
Industrial	0.00	0.00%	43.08	1.23%	136.11	1.34%	160.34	0.99%	190.96	1.05%
Institutional - Education	0.00	0.00%	0.00	0.00%	0.00	0.00%	921.17	5.70%	1,053.46	5.79%
Institutional - Other	2.50	0.47%	78.06	2.23%	170.69	1.69%	198.40	1.23%	227.44	1.25%
Mixed Use	0.00	0.00%	2,283.05	65.26%	4,945.77	48.85%	5,760.44	35.65%	6,499.19	35.73%
Total	530.45	100.00%	3,498.14	100.00%	10,124.80	100.00%	16,157.34	100.00%	18,187.52	100.00%

2.4 Discussion

This section discusses the key results from the road material stock analysis and sea level rise vulnerability mapping in Grenada. The implications of the methodology and results of this study for small island states are discussed. Limitations of this work and potential future work are also addressed.

2.4.1 Road material stocks and associated building services in Grenada

The total road material stock in Grenada in 2015 was estimated to be 4,375 kilo tonnes, equivalent to 40.96 t/capita. The total length of roads was about 1,594.52 km with an average material content of 2,744 tonnes per kilometer. Including road stocks in the total material stock (MS) estimation yielded a total material stock output of 18,387.40 kilo tonnes (172.13 t/capita). 24% of the materials were stocked in roads, while 76% of the materials were stocked in buildings. Aggregate materials stocked in roads accounted for 55% of total aggregate stocks in Grenada. Therefore, materials stocked within the road network comprise a large share of total material stocks in Grenada, which suggests that it is highly important for small island states to consider civil infrastructures (including transportation) when conducting material stock accounting. The exclusion of civil infrastructure in total material stock accounting may result in a significant underestimation and errors. A comprehensive and accurate material stock accounting is required for small island states to manage in-use materials, control material import and disposal flow, predict vulnerable stocks, develop future construction plans, and fulfill sustainable development goals.

For comparison, Tanikawa et al. (2015) estimated that in Japan, building stocks and road stocks comprised of about 43% and 26% of total material stocks respectively in 2010, followed by seaports (19%), and dams (8%). Noll et al. (2019) estimated that in the Greek island of Samothraki, materials stocked in buildings, roads, and ports accounted for 57.6%, 14.8%, and 27.4% of total material stocks respectively in 2016. Haberl et al. (2021) calculated the material stocks of buildings and infrastructures in Austria and Germany in 2018. The results showed that in Germany, building and road stocks made up roughly 63% and 33% of total stocks respectively, while in Austria, building and road stocks accounted for about 50% and 44% of total stocks respectively. Wiedenhofer et al. (2015) estimated that in the EU25, 39 billion tonnes of nonmetallic minerals were stocked in roads (128 tonnes/capita) and 35 billion tonnes of stocks were stocked in residential buildings (72 tonnes/capita) in 2009, compared to 93.39 tonnes/capita of stocks in residential buildings in Grenada (De Kroon, 2020). The proportion of road stocks in Grenada is lower than Japan and Europe but higher than the Greek island of Samothraki, which may be a product of differences in the maturity of road networks between developed areas and small islands. Geographic differences may result from the level of investment into transportation development, population distribution, topography, climate, the quality of data sources, and the local construction standards which affect the material intensity calculation. More studies of road stocks would be required in developing countries, especially small island states, to explore the socioeconomic drivers behind differences in road material stocks.

In terms of the average material stocks per kilometer, for the U.S., in 2015, the total length of roads was estimated to be 6.6 million kilometers and the number of materials stocked in each kilometer was 2,268 tonnes (Miatto et al., 2017). Recent research conducted by Nguyen et al. (2019) in the developing country of Vietnam, estimated the total length of roads at 217,000 kilometers and road material stocks at 2,660 million tonnes in 2012 (12,258 tonnes/km). Compared with these two countries, the quantity of road stocks per kilometer in Grenada (2,744 tonnes/km) is closer to the U.S. and significantly lower than Vietnam. This may be due to differences in road construction styles, pavement designs, and the material intensity development in different countries. For example, roadways in Vietnam are divided into four pavement types: soil paving (6.5 m of width typically), mixed stone and soil paving (9 m of width typically), stone paving (12 m of width typically), and asphalt concrete paving (26 m of width typically). The road pavement structure was divided into a surface layer (80 to 140 mm) and a base layer (300 mm; Nguyen et al., 2019). In comparison, in this study, the road network in Grenada was classified into Class-1A (13 m width), Class-1B (6 m width), Class-2 (5 m width), Class-3 roads (4 m width). The pavement structure is divided into the surface layer (50 to 150 mm), base layer (0 to 200 mm), and subbase layer (150 to 300 mm). In addition, it should be noted that the materials analyzed in Nguyen et al. (2019) and Miatto et al. (2017) differ from this study. Whereas these studies broke down road surface materials into gravel, sand, cement, and bitumen (i.e., asphalt) categories, aggregate, cement concrete, and asphalt concrete were categories adopted for Grenada. Asphalt (or cement) concrete is defined as a mixture of asphalt (or cement) and aggregates, which only comprises a small share of the concrete mixture.

In Grenada, 87% of roads were paved in 2015. Rigid concrete roads accounted for 61% of the total and were followed by flexible asphalt roads (26%). The percentage of asphalt paving roads is low compared to developed countries, such as the U.S., Canada, and the UK (over 94%; AIA, 2021; National Asphalt Pavement Association, 2011; Ontario Asphalt Pavement Council, 2017). According to Nguyen et al. (2019), the share of asphalt paved roads in Vietnam was 47% in 2008. According to MTPRC (2013), asphalt paved and concrete paced roads in China were about 15.1% and 39.0% of total roads in 2012. Although asphalt paved roads are safer for driving, quicker to install and repair, and more environmentally friendly compared to concrete paved roads, the high cost of road rehabilitation, the limited raw materials, the low traffic volume (especially in inland mountainous areas), and the high maintenance requirement limit the adoption of these practices in small island states (Atlantis Holdings Ltd, 2021; Ontario Asphalt Pavement Council, 2017). Therefore, only the regional roads in Grenada are fully paved with asphalt concrete, resulting in a lower proportion compared to other countries found in the literature.

Road stocks support the functioning of nearby building services by providing access, connecting supply chains, and facilitating the flow of goods, people, and materials. Therefore, road stocks are inherently related to the services provided by nearby buildings. The results of this study show that in Grenada, about 88% of the road stocks were associated with local residential buildings, followed by tourism (4%), commercial (2.5%), mixed use (the mixture of residential and commercial services, 1.9%), industrial (1.6%) and education (0.7%). Stocks related to residential, tourism, and commercial buildings occupied over 96% of total road stocks. It is not surprising that residential stocks comprise the largest proportion since living space is the basic need for human life. Tourism, education, construction, and commercial sectors are the major contributors to Grenada’s GDP and economic growth (Caribbean Development Bank, 2019; Government of Grenada, 2021). In 2020, the tourism sector and private education constituted 40.5% and 20%, respectively, of Grenada’s GDP before the COVID-19 island-wide lockdown (Caribbean Development Bank, 2021).

In this study, road stocks were linked to the provision of local services by calculating the ratio of services provided by surrounding buildings. This is a novel method developed in this study, which aims to evaluate the amount of road stocks used to support the access to local services and focuses on one of the basic functions of a roadway, which is providing access to properties. However, some high-level roads (e.g., regional roads) are designed primarily for facilitating traffic mobility and therefore may not be closely connected with the local building services sited along the road. In the absence of available detailed traffic statistics for Grenada, including source and destination information, this study was not able to, (a) assess how road stocks support traffic mobility or (b) evaluate the road stock productivity. Traffic mobility can be indicated by the volume of passenger (measured in passenger-kilometers), freight (measured in tonnes-kilometers), or vehicle traffic flow (measured in vehicle-kilometers) in a given time period. Stock productivity can be measured by dividing the volume of traffic flow by the amount of road stocks (Gassner et al., 2021; Nguyen et al., 2019).

Stock productivity can illustrate whether road stocks are used efficiently. Low productivity suggests the inefficient use of road stocks and more transport services can be provided, while high productivity suggests efficient or even overuse of road stocks. Areas with high material stock accumulation are not necessarily the ones with high productivity (Miatto, Dawson, Nguyen, Kanaoka, & Tanikawa, 2021; Nguyen et al., 2019). Understanding the road stock productivity is important for developing sustainable infrastructure construction and leveraging road stocks in small islands, and should therefore be explored in future sustainability studies of small island states.

2.4.2 Spatial distribution of road stocks

The spatial distribution maps illustrate that road stocks in Grenada are clustered in low-lying coastal areas. For Grenada, coastal zones are the major developing areas with rich resources and connections to marine trades and transport. The population density and the speed of economic development are significantly high and intense in coastal areas. Most of the major cities/towns (e.g., St. George’s, Grenville, Gouyave, Victoria, and Sauteurs), fishing villages, agricultural lands, and important infrastructures (e.g., roads, tourism resorts, and marinas) are situated in coastal areas (German Pilot Programme, 2018; Neumann, Vafeidis, Zimmermann, & Nicholls, 2015). These are the same areas that are most vulnerable to the effects of sea level rise.

Road stocks are most concentrated in the southwestern part of the island (i.e., in the St. George Parish). This is the most populous parish in Grenada where the capital of the country, St. George’s, is located. Two distinct hot spots of road stocks occur in the Town of St. George’s and the southwest corner of the parish near Grand Anse Beach. The pristine climate and views of the 3-km-long Grand Anse Beach on the southwest coast of the island attracts considerable numbers of global visitors every year (Marinas, 2021). The resort accommodations vary from private villas to luxury resorts and are clustered along the beach area, leading to comparatively higher road density and concentrations of road material stocks, especially related to tourism and commercial services. In addition, hot spots of education- and industry-related stocks can be observed in the southwest. Over 25% of the education-related road stocks are accumulated in the Enumeration District (ED) where St. George’s University is located.

Compared to the building stocks, the distribution of road stocks is more dispersed over the entire island. The elongated lines of road stock accumulations in the mountainous inland areas depict the main interior roads crossing different parishes and connecting the major towns of the island (e.g., St. George’s, Grenville, Gouyave). These road stocks are not only dedicated to meeting local transportation needs, but also effectively fuel commercial activity within urban areas, along coastal areas, and in the entire country.

Visualizing the spatial distribution of road stocks using GIS techniques enables decision makers to better understand the locations and distribution of in-use road stocks within the island’s socio-economic system. Stocks currently stored within the built environment can be considered as the source of material wastes and secondary resources. Understanding the status of in-use stocks could help decision makers better project construction and demolition wastes, manage the disposal and re-utilization of materials, and reduce environmental impacts and material import costs (Hashimoto, Tanikawa, & Moriguchi, 2009; Pauliuk & Hertwich, 2015). Knowing the spatial distribution of stocks is also a key step in vulnerability analysis. By integrating the spatial distribution map of material stocks with a risk map of sea level rise, the most vulnerable areas of stocks can be identified. This can help to inform and enhance coastal preparedness, planning, and decision making for mitigating the adverse impacts of climate change and building resilience to climate risks.

2.4.3 Sea level rise vulnerability mapping

This study maps vulnerable road material stocks in different future sea level rise (SLR) scenarios in a case study area of St. George’s Harbor. The results show that a 1.0 m rise in sea level could affect most of the roads in Carenage and the yacht harbour (i.e., the north and south branches of St. George’s Harbour). A sea level rise of 1.5 m or more could cause most of the roads near the shoreline of St. George’s Harbor to be flooded, including roads near the Tanteen sports ground and T.A. Marryshow College. Under the 2.0 m sea level rise scenario, over 5,220 meters of coastal roads would be exposed and about 18,188 tonnes of road stocks would be at risk. Road stocks support the building services of residential stocks, mixed use (commercial and residential), commercial, and transportation (e.g., marinas, ports, and docks) would be most at risk since St. George’s is the largest city, the primary economic hub, and the largest harbour on the island. According to the SROCC report and recent published papers, the global mean sea level would potentially rise by 1.0 m or even 2.0 m by the end of this century under a high emission scenario (Bamber et al., 2019; Grinsted & Christensen, 2021; IPCC, 2019). This means that if protection strategies or relocation plans are not implemented by 2100, most of the road stocks near the shoreline of St. George’s Harbor would likely be exposed to sea level rise and inundated.

According to the Climate Change Risk Atlas for Grenada and Grenada National Climate Change Policy (2017-2021), due to sea level rise and increasing intensity of extreme weather events, Grenada has experienced severe losses in coastal resources, including natural resources and man-made infrastructure (Government of Grenada, 2017b; Simpson et al., 2012). Potential sea level rise and extreme weather events in the future place significant pressure on Grenada's coastal area management, since the country's economy, lifestyle, and culture are highly dependent on the health of coastal areas (Government of Grenada, 2015). In 2015-2016, the government of Grenada outlined the Integrated Coastal Zone Management (ICZM) framework and approved the Coastal Zone Management Policy which was developed through collaboration with the Caribbean Aqua-Terrestrial Solutions (CATS) and the Integrated Climate Change Adaptation Strategies (ICCAS) program (Government of Grenada, 2015). One of the goals in the ICZM policy is to reduce coastal vulnerability, enhance coastal resilience to natural risks, and promote sustainable coastal communities by utilizing vulnerability reduction approaches in the coastal management process (German Pilot Programme, 2018; Government of Grenada, 2015). Vulnerability or risk mapping is one of the key strategies for achieving this goal. These methodologies can clearly identify and assess vulnerable areas or infrastructure, inform future planning or decision making on construction in coastal areas, and help develop stabilization solutions to improve coastal sustainability and resilience.

This study not only maps vulnerable road stocks in Grenada under different sea level rise scenarios, but also showcases the viability to improve current vulnerability mapping using LiDAR data in a small island state case study. Previous studies on vulnerability mapping in small island states mainly relied on intensive field surveys or global and national DEMs that have coarse resolution and errors. This study utilizes high-resolution LiDAR data for creating a Digital Terrain Model (DTM) that provides highly accurate elevation information. This LiDAR data is then integrated with other sources of GIS data to map vulnerability. This significantly improves the resolution of the bare-Earth surface model, enhances the accuracy of terrain mapping, and reduces the time and labour cost involved with analyzing a large study area, such as the entire island of Grenada.

2.4.4 Limitations and future work

As mentioned in Section 2.2.1.1.1 , Grenada does not have an up-to-date road classification system with consistent nomenclature available (Grenada Ministry of Infrastructure Development, 2020). Therefore, the road classification system developed in this study was derived from the combination of road network GIS data on CHARIM, road classifications used by Ministry of Infrastructure Development, Government of Grenada, and information on road pavement structures. The road types and nomenclature applied in this study are developed for the material stock estimation for Grenada, which are not consistent with the classification systems used by some government departments (e.g., the Lands Division at the Ministry of Agriculture and the Physical Planning Unit) in Grenada. Significant revision and update of the road classification and nomenclature system are recommended by the government of Grenada in order to better manage the road network, collect more consistent data, and strengthen cooperation between different departments. Another problem is that the road classification system in this study was developed and confirmed using secondary data, satellite images, street view photos, and observations. Primary field work is required to further validate the accuracy of this classification system; however, due to the travel restrictions related to the COVID-19 pandemic, all analyses were conducted remotely without an on-site visit. If possible, field work could be conducted in the future to validate the classification system and to conduct a comprehensive accuracy assessment.

Small island states often face the problem of limited data availability, especially spatial data sources. In this study, the available road network data for Grenada only covered the main island of Grenada and has not been updated since 2015. Many small access roads and new roads are not included and would affect material stock estimates. Therefore, it is recognized that the road material stock account for Grenada estimated in this study is not based on up-to-date data and does not cover the entire country. The total road stock account may be underestimated as a result. It is noted that in recent years, Grenada’s economic growth has been heavily dependent on the expansion of tourism and construction (Caribbean

Development Bank, 2019, 2021). New construction of roads related to new developments could result in large material accumulation within the socio-economic system, which may not be captured in the current road stock account. If complete and up-to-date road network data for Grenada are available in the future, the material stock could be updated using the same methodology tested in this study and compared with previous estimates. Furthermore, there may be more potential drivers behind changes in material stocks over time, which could be explored, especially once research travel is permitted to conduct on-site fieldwork and interviews with local officials.

Another potential limitation of this study is that composite pavement types were not considered in the road classification system and material intensity typologies. A composite pavement type is one where an asphalt surface is placed over an existing cement concrete surface. This is a common approach for road rehabilitation and maintenance. The high degree of similarity between the surface layers of the composite pavement and flexible asphalt pavement makes it hard to distinguish between the two pavement types from satellite imagery without having additional data or supplementary resources available. Therefore, only the flexible asphalt pavement, rigid concrete pavement, and unpaved road categories were considered in this study. Composite paved roads are potentially misclassified into asphalt paved roads, which could result in errors in the material stock calculation. In addition, since distinguishing between different road pavement types was conducted through visual inspection of satellite imagery and available on-site videos and photos without field verification, uncertainties in material stock estimates are inevitable. Future studies could potentially improve the current road classification system and material intensity typologies by considering composite pavement types.

The sea level rise vulnerability mapping produced in this study was only conducted for a smaller sample site due to the extensive LiDAR data processing time required and limited computer processing capacity that was available. Future studies could conduct the same analyses on other study sites, such as important beach or coastal areas, or if computing resources permit, expand the study to cover the entire island. Grand Anse Beach is one of the main coastal areas where a large accumulation of tourism stocks are located and are highly vulnerable to climate change. Simpson et al. (2012) predicted that 77% of the beach area in Grand Anse Beach may be lost under a 2.0 m sea level rise scenario, which would impact most tourism resorts and hotels in the area. Grand Anse Beach is identified as a potential study site for vulnerability mapping, especially if LiDAR data for this coastal area can be acquired. Due to the lack of hydrological models and tide gauge data, the base water surface used for sea level rise simulation was derived from a single value (i.e., the average water level along the St. George's coast). In the future, more accurate water surface modelling can be achieved if more detailed hydrological data were available, which would also help to improve mapping of sea level rise.

This study developed a novel methodological approach for Grenada to estimate, map, and analyze in-use road material stocks. It showcases the feasibility of non-building material stock analysis in the small island states context and indicates the important role of road material stocks in island countries' socio-economic metabolism and sustainable development. Moreover, this study demonstrates that data constraints are the main challenge for current material stock accounting and vulnerability assessment in small island states. It is highly recommended for the local government to collect, organize, and coordinate data to be standardized and updated systematically. With reliable and up-to-date data sources available, more accurate and comprehensive material stock estimates can be produced in the future aiding in sustainable resource management and climate change adaptation planning.

Chapter 3

Utilizing LiDAR Data in 3D GIS Modelling of Building Material Stocks

3.1 Introduction

In-use materials stocks play an important role in socio-economic metabolism since they can shape resource cycling by affecting the input demand for raw materials and the disposal of environmental waste. Rapid urbanization, industrialization, and population growth have resulted in massive material stock accumulation in built environments and huge environmental pressures including greenhouse gas emissions, toxic or harmful wastes, resource scarcity, and land use conflicts (Augiseau & Barles, 2017; Fu, Zhang, Deng, & Daigo, 2021; Tanikawa et al., 2021). Quantitative analysis of in-use material stocks is necessary for understanding the status of accumulated materials and improving sustainable development strategies (Tanikawa et al., 2021). Among all types of stocks, building material stocks are considered to be one of the largest natural resource repositories and has become the focus of previous material stock research (Fu et al., 2021). A few studies have been dedicated to quantifying building material stocks in developing countries, such as small island states, which are in a period of rapid urbanization with large-scale ongoing constructions and development. Small island states are particularly vulnerable to climate impacts due to their remoteness, limited resources, and unique socio-economic characteristics.

Research on building material stocks on small island states is severely limited due to data availability, including having access to accurate building height information for stock estimation. Generalizations are adopted for estimates. For example, previous research has assumed that all buildings of the same class share the same height (Symmes et al., 2019). This assumption ignores the heterogeneity among buildings and fails to capture height information for each building. This study aims at addressing this problem by incorporating the use of LiDAR data in estimating building height and material stocks. This study combines GIS footprint data with LiDAR data to generate high-resolution building height estimates and utilizes LiDAR-derived height estimates in quantifying building stocks. 3D building models and a 3D WebGIS application for Grenada integrating material stocks with 3D city models are developed. Such geospatial methods and products provide policy makers and the general public with new visualization tools to investigate and assess material stocks from a 3D perspective.

3.2 Methodology

This section details the methodological approach adopted in this study and a workflow is shown in Figure 3.1. Each step in the diagram is explained in the subsequent methodology sections. Section 3.2.1 explains the building height estimation and building stock estimation approaches employed for the case study of Grenada. Section 3.2.2 describes how to assess the differences between new building material stock estimates and previous building stock estimates from De Kroon (2020). Sections 3.2.3 and 3.2.4 illustrate the processes of creating 3D building models and developing the WebGIS application.

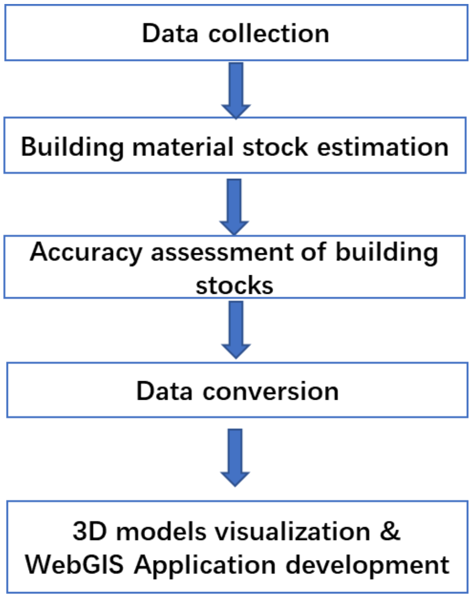


Figure 3.1: *Methodology workflow for Chapter 3.*

3.2.1 Methodology of building material stock estimation

The workflow of estimating building stocks is shown in Figure 3.2 Since this study aims to assess how using accurate heights of buildings in building stock calculation can improve estimates, this part of methodology is based on previous research by De Kroon (2020) and Rob Symmes et al. (2019). Previous studies calculated the building material stock by multiplying the material intensity coefficient of each occupancy class by the number of floors assumed for each class and the gross floor area of each building. In this study, the accurate building height of the individual building was obtained using LiDAR data and the Gross Volume (GV) was employed as the physical size of the building to estimate the building stock, which can better capture the real building geometry and improve material stock estimation. Due to the limited availability of LiDAR data and long data processing time required, the building material stock estimation focused on a smaller subarea of Grenada as a test case or proof-of-concept. This area was selected to be St. George's, where the most built-up and developed areas of the island are located and a large amount of material stocks are accumulated. Four tiles of LiDAR data (covering about 3.87 km^2) were used, and the location of the tiles is shown in the previous Figure 2.7 (refer to Section 2.2.4).

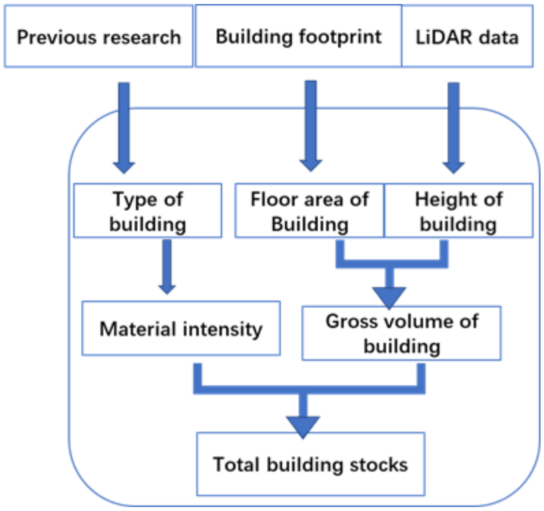


Figure 3.2: *Building stock calculation workflow.*

3.2.1.1 Building classification and material intensity

The first step of material stock estimation was to classify buildings into different classes, so-called occupancy classes. Each occupancy class shares a similar construction style and material composition and is assigned a material intensity (MI). In this study, the occupancy classification and the material intensity (MI) were adapted from previous research (see Appendix B; De Kroon, 2020; Symmes et al., 2019). Symmes et al. (2019) developed the occupancy classification system for Grenada based on footprint data, land use, location and other information and classified buildings into 25 classes. De Kroon (2020) assessed the classification results through fieldwork and reclassified several buildings. Since accurate building height for each building was unknown in previous research, the gross floor area (GFA) was used, and the material intensity was measured in kg/m^2. In this study, the gross volume was used to represent the physical size of the buildings. This entails converting the material intensity to kg/m^3 by dividing the value of the material intensity by the average height of one floor (10 feet/3.048 m adopted by Symmes et al., 2019). The final material intensity typologies are shown in Table B.2 (see Appendix B).

3.2.1.2 Building height estimation using LiDAR data

To obtain the actual height of the individual building, 2D building footprint data were integrated with elevation data from the LiDAR dataset. 2D building footprint polygons were used as the building boundaries and LiDAR points within building footprints which represent the building rooftops were used to estimate building heights. As discussed in the literature review (Section 1.2.3), raw LiDAR points within the footprint boundaries did not necessarily represent building rooftops, so the raw LiDAR point cloud had to be processed and only rooftop points were selected for further analysis. The LiDAR data used in this study were already processed by the data provider and classified into the ground, building, vegetation, and water points using filter algorithms in Terrascan software. Outliers that were isolated or clearly higher than surrounding points were first filtered out and then ground points were classified by constructing the triangulated surface model iteratively. Building points, referring to the building rooftop points, were classified by identifying planar surfaces. The classification results were manually checked and corrected (Government of Grenada, 2017a). To combine LiDAR data and building footprint data for building height estimation, two main steps were required: extracting LiDAR building points within the building footprints (refer to Section 3.2.1.2.1) and obtaining building heights through the statistical analysis of the extracted LiDAR building points (refer to Section 3.2.1.2.1).

3.2.1.2.1 Building footprint adjustment and building point extraction

Due to the inconsistency between the building footprint data and LiDAR data, the positions of footprint polygons deviate from the actual building boundaries in the orthophoto as well as the LiDAR building points. Therefore, before extracting LiDAR building points within building footprints, the footprint polygons were first adjusted to match the building boundaries in the orthophoto. Since the offsets between footprint polygons and the actual building boundaries were not consistent throughout the study site, the adjustment had to be conducted manually batch by batch using the Spatial Adjustment tool. After the adjustment, LiDAR building points within the building footprint polygons were clipped and extracted for the building height calculation in the next step.

3.2.1.2.2 Building height calculation and validation

The height of a building is considered to be the height difference between the roof and the ground level. Before deriving building heights from the extracted LiDAR building points, the points were normalized by the height of the nearest ground-classified point to provide the height above ground. According to Park and Guldmann (2019), among all different types of statistical measures used in building height estimation, average and median heights of LiDAR building points could better represent building heights. Thus, the average and median heights of the LiDAR building points were tested using 30 true building height measures from previous fieldwork conducted by De Kroon (2020). The mean absolute error (MAE) and root mean squared error (RMSE) were used to assess the accuracy of height estimates. The equations of MAE and RMSE are as follows:

$$\mathrm{MAE} = \frac{1}{n}\sum_{j=1}^{n}|y_j - \hat{y}_j| \tag{5}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(y_j - \hat{y}_j)^2} \tag{6}$$

where y_j is the *j*th height estimates, $\hat{y}_j$ is the *j*th true building height, $|y_j - \hat{y}_j|$ is the absolute difference, *n* is the total number of selected buildings (Roy, Das, Ambure, & Aher, 2016). MAE and RMSE are both negative-oriented scores, where lower values are desired (Harmel et al., 2014). The comparison of the accuracy of the height estimates is shown in Table 3.1 below. It is shown that height estimates from LiDAR points had higher accuracy compared with the general height assumption for each building class used in previous material stock research (De Kroon, 2020; Symmes et al., 2019). This means that the use of LiDAR data in building height estimation could better represent the actual shape of the building and improve building physical size calculation. Moreover, average heights had better performance than median heights (both MAE and RMSE are smaller), so the average heights of extracted LiDAR building points were adopted as the final building height estimates.

Table 3.1: *Comparison of the accuracy of height estimates.*

Statistical measure of building height	MAE (m)	RMSE (m)
Average height of LiDAR building points	1.01	1.27
Median height of LiDAR building points	1.20	1.39
Height assumption for building occupancy class	2.13	2.58

3.2.1.3 Building material stock estimation

The material stocked in buildings was calculated by:

$$MS_i = \textstyle\sum_{OC} GV_{OC} \times MI_{i,OC} \tag{7}$$

where MS_i is the total building stock of material i; GV_{OC} is the gross volume of all buildings in occupancy class OC; $MI_{i,OC}$ is the material intensity (kg/m^3) of material i in occupancy class OC (Symmes et al., 2019).

The gross volume of the building is calculated by:

$$GV = Building\ height\ estimate\ \times Footprint\ area \tag{8}$$

3.2.2 Accuracy assessment of building material stock estimation

The new building stock estimates of the subarea were compared with the related building stock estimates calculated by De Kroon (2020) to conduct an accuracy assessment. The differences between both datasets show how using accurate building heights derived from LiDAR data in material stock estimation can improve the results and by what range or magnitude.

3.2.3 Data format conversion and 3D building models

Since the building footprints for Grenada are originally in 2D Shapefile format, the FME software was used to convert 2D shapefile to 3D CityGML models based on building height information. 3D building models cover the main island of Grenada, and the data size was too large for management and visualization; therefore, 3D building models were divided into six parts covering six parishes. The workflow of the data transformation in FME is shown in Figure 3.3. The first step after the data input was to extrude the 2D building footprint using building heights. Since building footprints for Grenada only had the number of stories available, the building heights were estimated by multiplying the number of stories by the height (10 feet) of each storey (Symmes et al., 2019). The next step was to tag the CityGML features with the geometry role and LoD name so they can be written out correctly. Due to the limitation of footprint data, only LoD1 building models were created, and all buildings were assumed to have only flat roofs. In the CityGMLGeometrySetter transformer, CityGML LoD Name was set as “lod1Solid” and the feature role was set as “cityObjectMember”. The attributes (e.g., occupancy classes, heights, material stock estimates, service types, etc.) in original data were also included in the CityGML data. After setting the attributes, 3D building models in CityGML data format were exported.

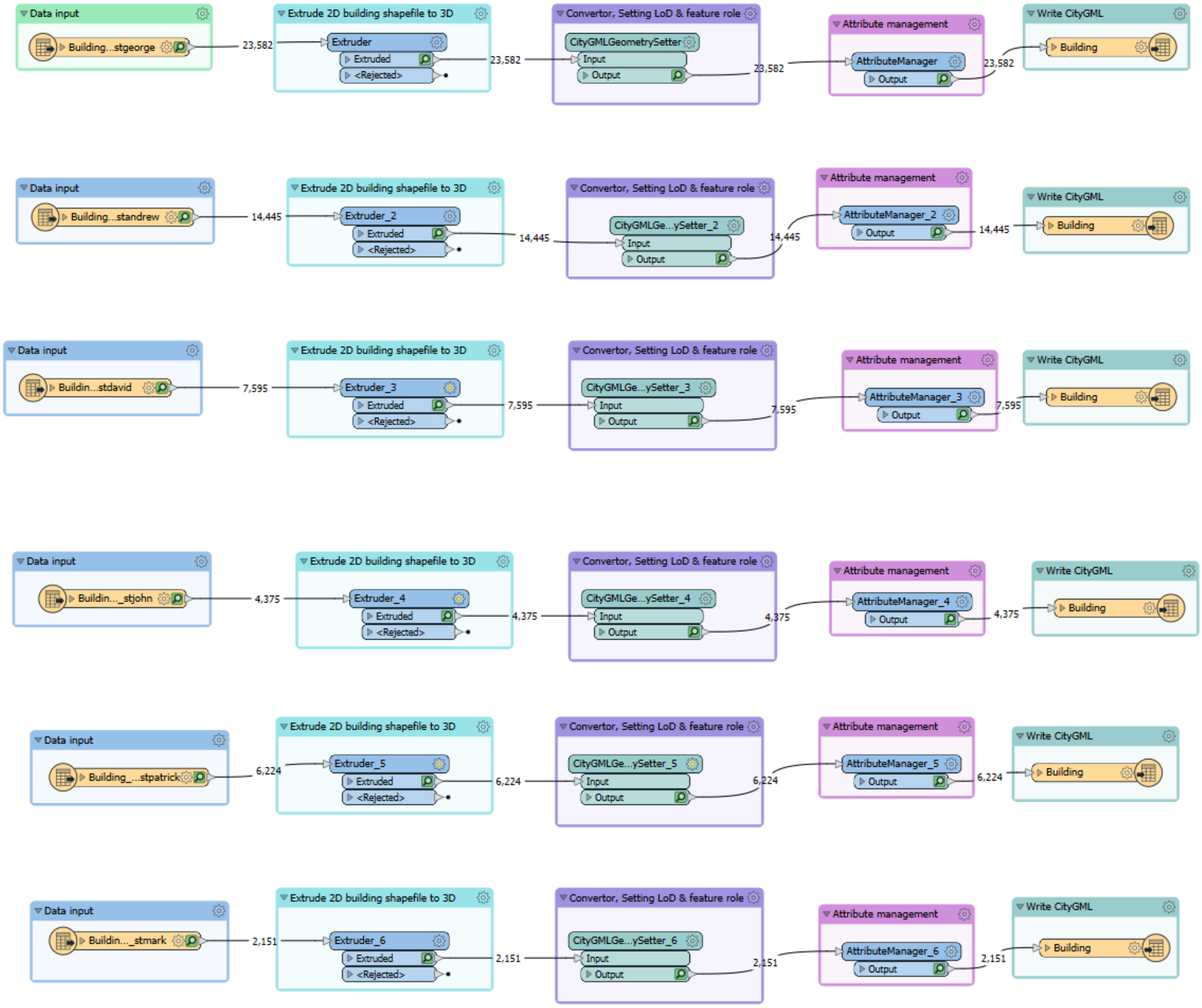


Figure 3.3: *Workflow of 3D building model transformation in FME.*

3.2.4 3D models visualization and WebGIS application development

In order to aid municipal administrations and local citizens in accessing the 3D models and material stock data, a 3D web-based application was developed using ArcGIS

API for JavaScript version 4.21. ArcGIS API for JavaScript developed by ESRI is an Application Programming Interface (API) between the client and ArcGIS server and is based on JavaScript. The client can easily make a request through the API and obtain the services provided by ArcGIS server, such as embedding interactive maps in web applications, performing GIS visualization and analysis, and querying spatial data (ESRI, 2021b).

First, all required data (e.g., building footprints, parish boundaries, land use maps, road network data, etc.) were grouped into a geodatabase and uploaded to ArcGIS online so that they could be used as the feature layers in the web application (or web app). Second, the 3D scene was developed, and all feature layers were added and styled. 3D Buildings were coloured based on occupancy classes and extruded based on building heights. Pop-ups were set to show further attribute information about the buildings and material stocks. The road network data were coloured based on the road hierarchy with pop-ups showing road material stock information. The river map, transportation port location map, boundaries map (e.g., country boundaries, parish boundaries, census enumeration district boundaries), and land use map were also added to serve as a reference layer.

Third, several widgets were added to provide more functionality (e.g., Zoom in/out, Pan/Rotate, Reset Orientation, Fullscreen, Basemap Gallery, Search, Layer List, Legend, Locate, Home etc.). The Zoom in/out, Pan/Rotate, Reset Orientation, Fullscreen widgets enable users to adjust the view of map/scene. The Basemap Gallery widget allows users to view data from different perspectives based on different basemaps (e.g., OSM, Streets, Imagery); for example, if they want to know where the building with the highest material stocks is located, it would be better to use OSM or streets map because it can show locational information. The Search widget offers a quick way of finding specific locations. The Layer List and Legend widgets together provides users the information of layers in the app. The Locate widget can guide the view to where users locate, while the Home widget would bring users back to default view. Fourth, a customized analysis widget was developed to query building material stock statistics and assess vulnerable building stocks. Finally, the web app was styled using JavaScript, HyperText Markup Language (HTML) and Cascading Style

Sheets (CSS) and an introductory pop-up modal box showing brief introduction and credits. The final web application can be published online or embedded within a website.

3.3 Results

The following sections describe the results of this study. Section 3.3.1 provides a comparison between LiDAR-derived building height estimates from this study and assumed building heights from a previous study by De Kroon (2020). Sections 3.3.2 and 3.3.3 compare the recalculated building material stocks with previous building stock estimates (De Kroon, 2020). 3D building model and 3D WebGIS application results are shown and explained in Sections 3.3.4 and 3.3.5.

3.3.1 Comparison of height estimates

Table 3.2 compares the assumed building heights previously from De Kroon (2020) and LiDAR-derived building height estimates in the sample site of St. George's in this study. Only buildings with height offsets larger than 0.1 m were accounted for due to the LiDAR vertical accuracy. MAE is the mean absolute difference between assumed and LiDAR-derived values as follows:

$$MAE = \frac{1}{n} \sum_{j}^{N} \left| HA_j - HL_j \right| \tag{9}$$

RMSE is the root mean squared difference calculated by equation 10.

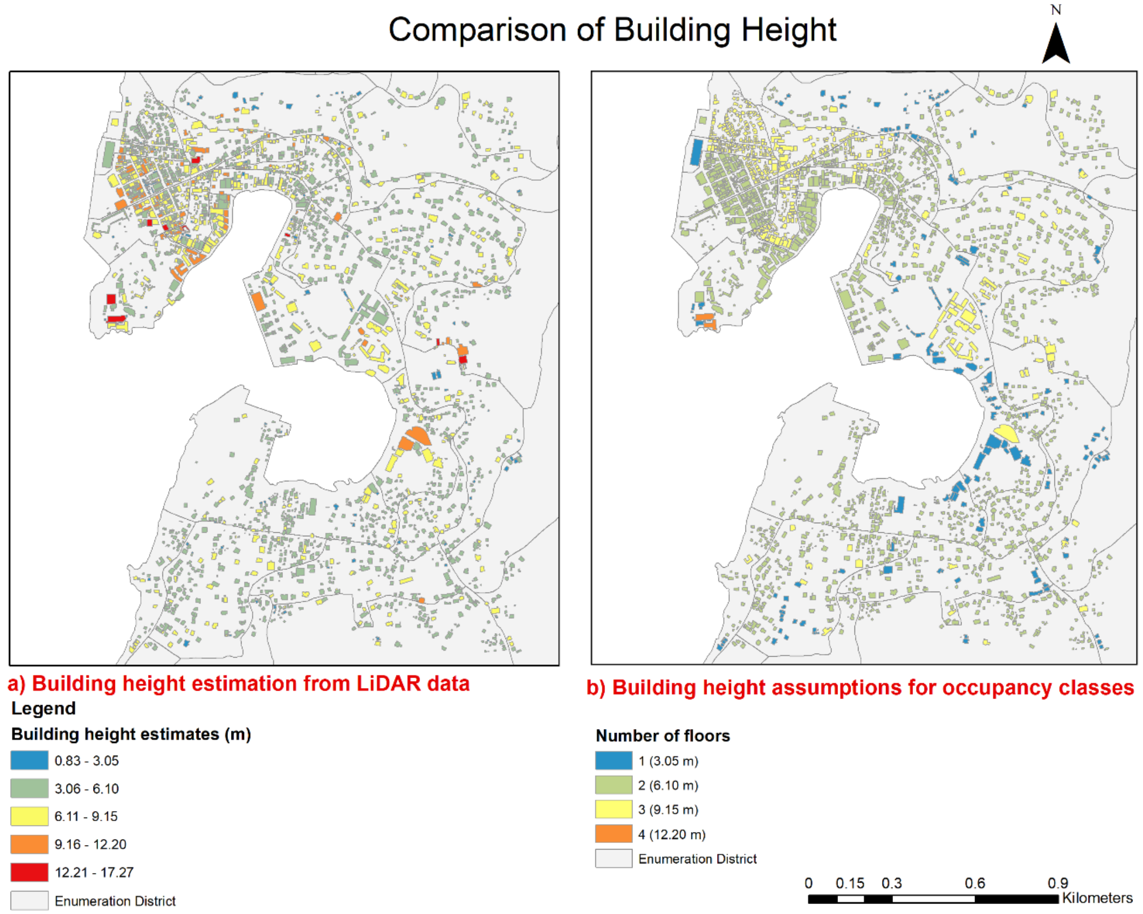
$$RMSE = \sqrt{\frac{\sum_{j}^{N} (HA_j - HL_j)^2}{n}} \tag{10}$$

where n is the number of building footprints, j is the index of footprint, HA_j is the assumed building height from previous research, HL_j is the LiDAR-derived building height estimate.

The results show that using LiDAR data produced fairly different building height values as compared with the values assumed based on occupancy classes. Over 96% of the buildings experienced variations in height and the MAE and RMSE were about 2.15 m and 2.67 m respectively. Figure 3.4 presents the spatial distribution of LiDAR-derived building height estimates compared to assumed building heights from De Kroon (2020). In this map, the building height assumptions used by De Kroon (2020) are classified into four classes based on the number of floors. The average height of one storey was about 10 feet or 3.05 m (De Kroon, 2020; Symmes et al., 2019). Therefore, buildings with one floor (i.e., single-storey buildings) were about 3.05 m; buildings with two floors (i.e., two-storey buildings) were about 6.10 m, and the following classes are similar. For comparison, the LiDAR-derived height estimates are classified into five classes and the values of the upper end of the classes are set as 3.05 m, 6.10 m, 9.15 m, 12.20 m, and the maximum height value. Figure 3.4 (a) clearly shows that using LiDAR data in height estimation can better represent the heterogeneity of building heights. In previous research (De Kroon, 2020; Symmes et al., 2019), the building height was assumed based on occupancy classes, which means that buildings in the same class shared the same height value. This can be seen in Figure 3.4 (b) that buildings with the same number of floors (in the same colour) tend to be clustered showing homogeneity. In addition, previous research assumed four floors as the maximum building height (about 12.20 m); however, buildings with a height over 12.20 m actually do exist, such as the St. George's General Hospital which has five floors and is over 17 m in height. LiDAR-derived height estimates can better capture such “outliers” and significantly enhance the accuracy of such estimates.

Table 3.2: *Comparison between assumed building heights (De Kroon, 2020) and LiDAR-derived building height estimates in the sample site.*

# of buildings with offsets (>0.1 m)	**MAE (m)**	**RMSE (m)**
2291 (96.6%)	2.15	2.67



a) Building height estimation from LiDAR data

b) Building height assumptions for occupancy classes

Figure 3.4: *Spatial distribution of (a) LiDAR-derived building height estimates compared to (b) assumed building heights from De Kroon (2020) in the sample site.*

3.3.2 Comparison of building material stock estimation

The total amount of building material stocks in the sample site of St. George’s were recalculated using the LiDAR-derived building heights. As shown in Table 3.3, the new total amount of building stocks was estimated to be 1,192.99 kilo tonnes and the sum of differences was about 57.08 kilo tonnes compared to the estimate (1,250.07 kilo tonnes) from De Kroon (2020). The MAE and RMSE between two total stock estimates were about 168 tonnes and 445 tonnes respectively. MAE refers to the mean absolute difference between the material stock estimate from De Kroon (2020) and the material stock estimate using LiDAR-derived heights (Equation 11).

$$MAE = \frac{1}{n} \sum_{j}^{N} \left| MSA_j - MSL_j \right| \tag{11}$$

RMSE is the root mean squared difference calculated by Equation 12.

$$RMSE = \sqrt{\frac{\sum_{j}^{N} (MSA_j - MSL_j)^2}{n}} \tag{12}$$

where n is the number of building footprints, j is the index of footprint, MSA_j is the material stock estimate from previous research, MSL_j is the material stock estimate using LiDAR-derived heights.

The results illustrate that using height assumptions based on occupancy classes in material stock accounting resulted in overestimation in building stock estimates compared to using LiDAR-derived heights. The most discrepancy in material stock estimates could be found in concrete with the highest MAE and RMSE since concrete is the main material used in building construction. Figure 3.5 illustrates the spatial distributions of differences in building stock estimates. The majority of buildings (74%) had higher stock estimates in De Kroon (2020) compared to this study. High discrepancy of stock estimates occurred in buildings with larger footprint areas, such as T.A. Marryshow Community College, St. George's University General Hospital, QualiTech Medical Laboratory Inc., and Bryden & Minors Office Equipment Division.

Table 3.3: *Differences between old building material stock (MS) estimates from De Kroon (2020) and new building material stock estimates by materials (tonnes) in the sample site.*

Material type	Aggregate	Timber	Steel	Concrete	Total
Old MS - new MS	6,250.54	2,987.47	775.81	47,063.61	57,077.42
MAE	33.74	5.44	2.11	126.52	167.84
RMSE	94.89	11.59	5.50	334.74	445.26

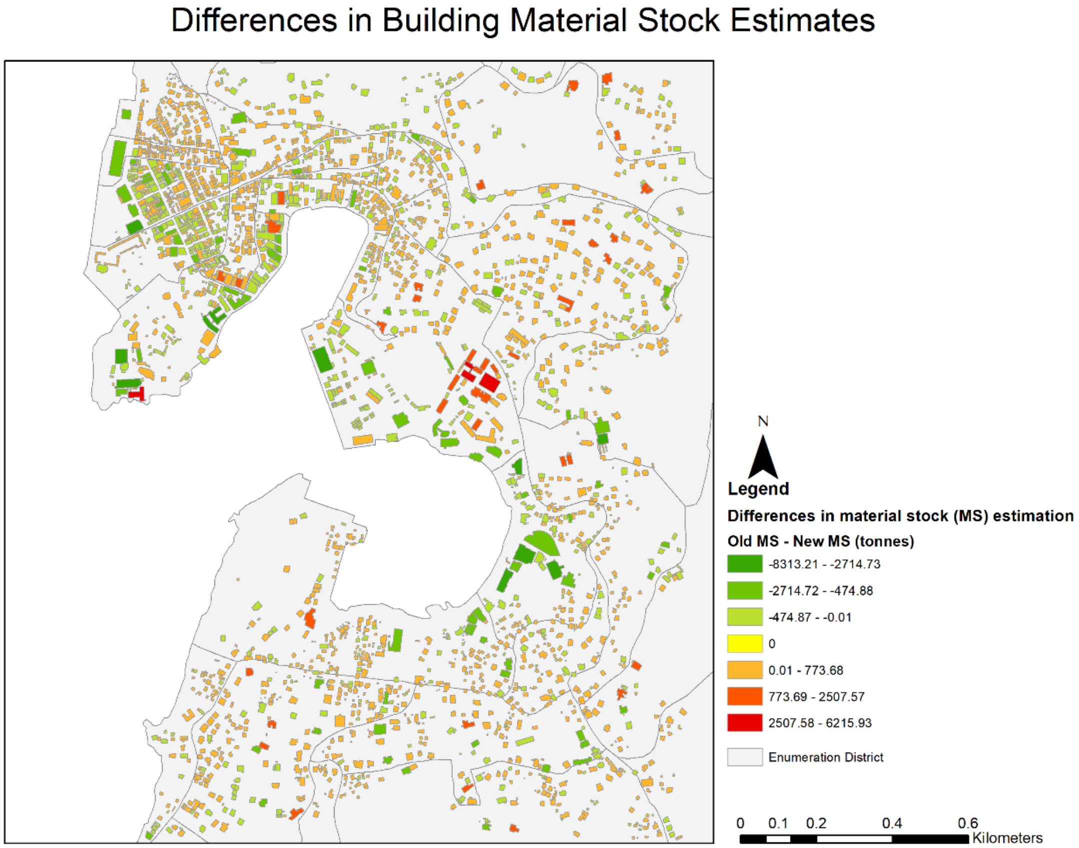


Figure 3.5: *Spatial distribution of differences between old building MS estimates (estimates from De Kroon (2020)) and new building MS estimates in the sample site.*

3.3.3 Comparison of building material stock by service type

Table 3.4 below compares the differences between building stock estimates by service types. The most significant sum of differences of stock estimates occurred in the residential sector (58 kilo tonnes), followed by the commercial sector (46 kilo tonnes), and mixed use sector (30 kilo tonnes). However, the highest discrepancy of stock estimates in each building (MAE or RMSE) was observed in the health sector (1,685 tonnes), followed by industrial, commercial, and institutional sectors.

Table 3.4: *Differences between old building MS estimates (estimates from De Kroon (2020)) and new building MS estimates by service types (tonnes) in the sample site.*

Service type	Sum (old MS - new MS)	MAE	RMSE
Health	-2,888.90	814.12	1,684.96
Tourism	8,182.86	593.36	782.25
Residential/Shelter	57,516.58	78.64	137.34
Cultural	-5,052.35	201.40	439.76
Recreational	-2,913.70	135.81	210.64
Transportation	-4,174.92	248.77	653.32
Commercial	-45,896.53	642.38	1,373.91
Industrial	-4,149.87	1,383.29	1,504.55
Institutional - Education	28,656.25	812.95	1,353.15
Institutional - Other	-2,285.88	616.37	1,096.41
Mixed Use	30,083.88	161.07	341.54

3.3.4 3D building model

Figures 3.6 and 3.7 show examples of the 3D building models developed for Grenada in CityGML format using the FZKViewer software. CityGML is the most popular international standard and exchange format for 3D city models and can represent both semantics (i.e., the meaning of the components and attributes and the relationships between components) and geometry of the models (Kolbe, Donaubauer, Kolbe, & Donaubauer, 2021). In this study, real-world objects are modelled as the building feature type at the semantic level, with attributes including the use type, occupancy class, building code, number of floors, height assumption, material intensity coefficient, material stock, service type, and other properties (as shown in Figure 3.8). The geometry is set as LoD1 solid block model which only has a flat roof. 3D CityGML building models developed in this study not only represent the buildings in Grenada from the 3D perspective but also integrate material stock and service information with the model, which can enhance data visualization and aid in future material stock management and urban planning.

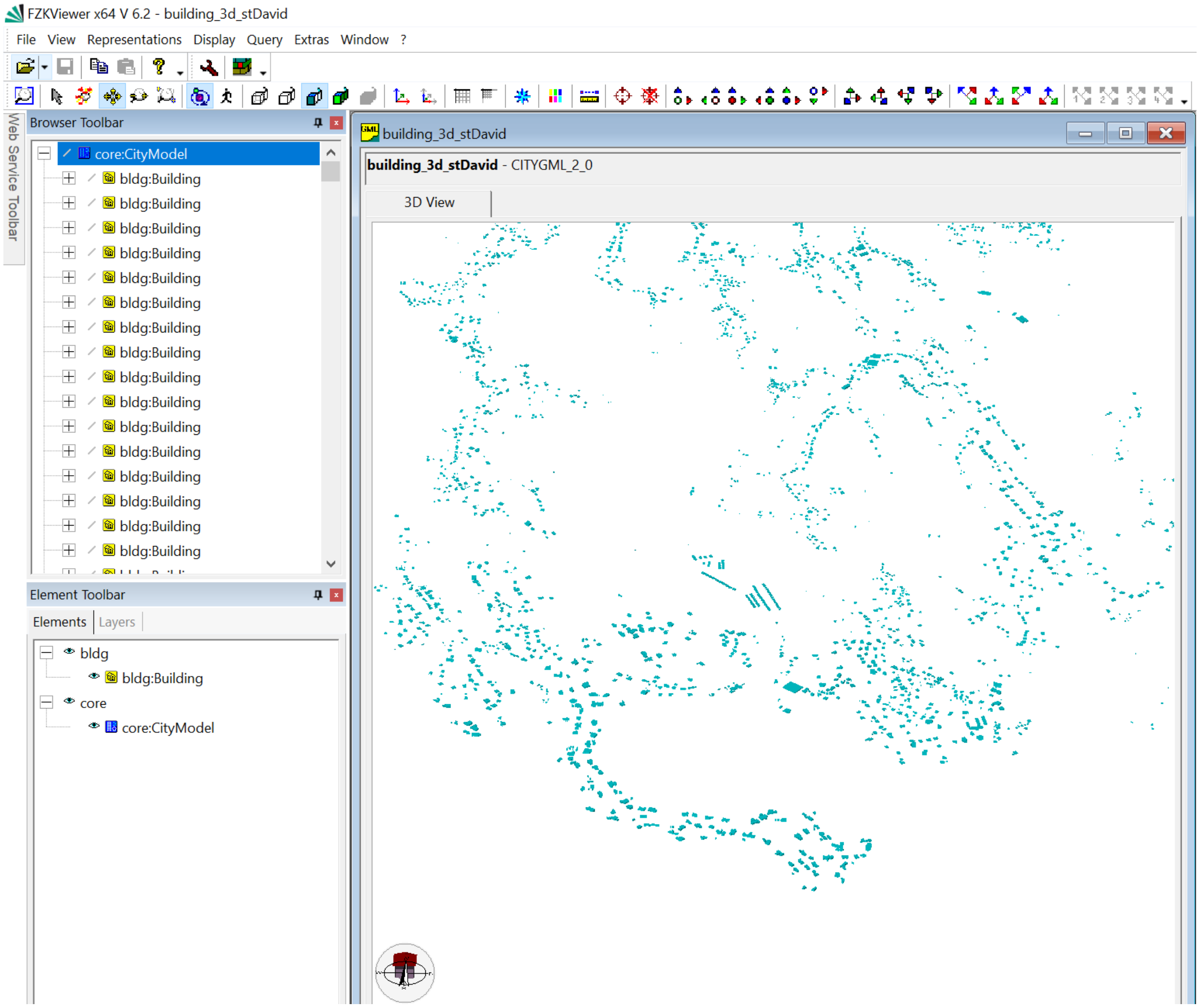


Figure 3.6: *Example of 3D CityGML building models for St. David Parish, Grenada.*

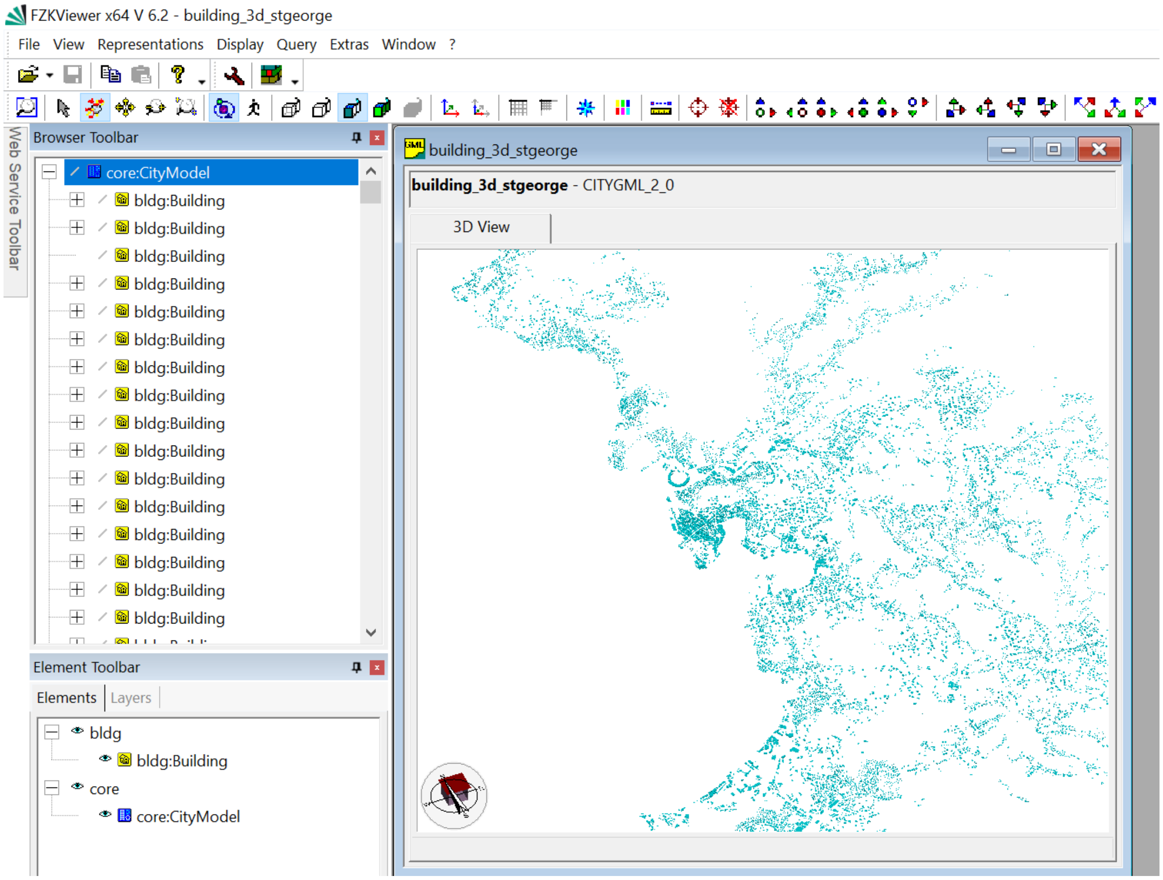
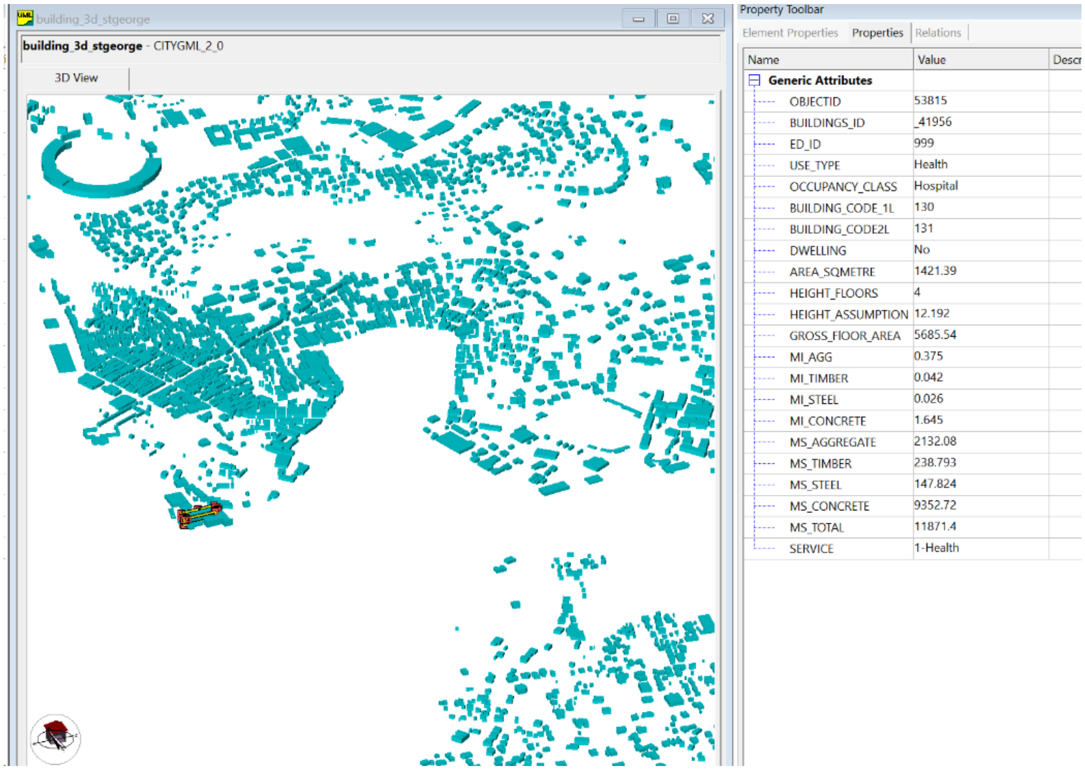


Figure 3.7: *Example of 3D CityGML building models for St. George Parish, Grenada.*

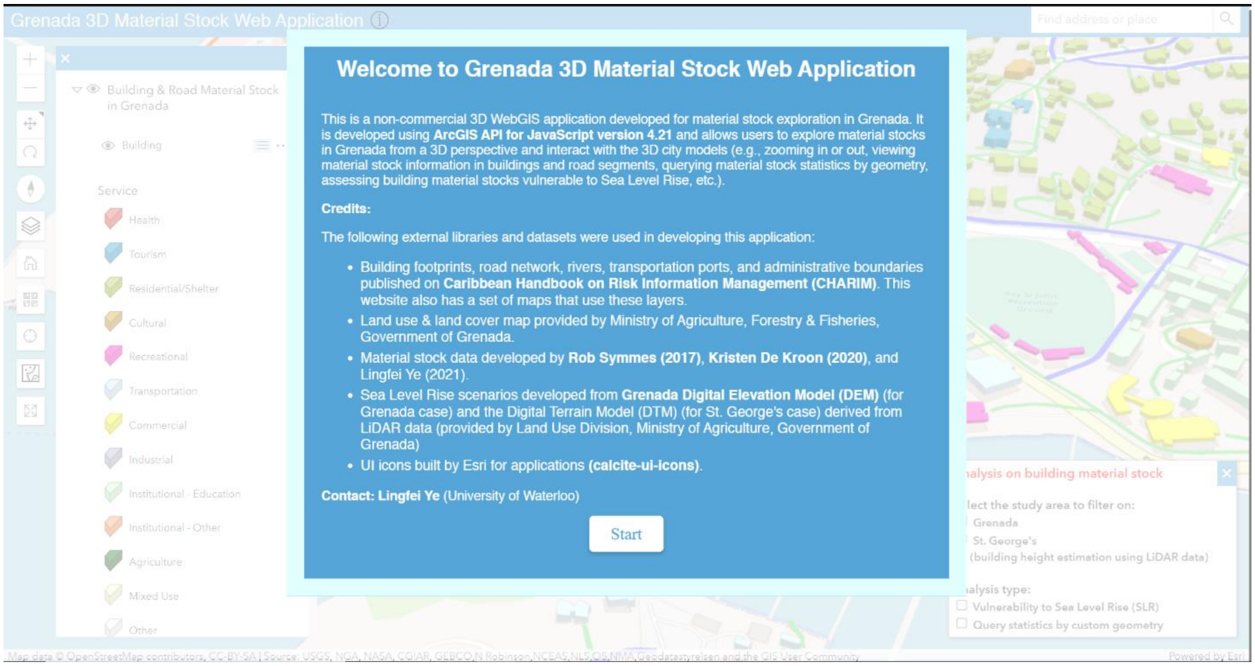


Name	Value	Descr
Generic Attributes		
OBJECTID	53815	
BUILDINGS_ID	_41956	
ED_ID	999	
USE_TYPE	Health	
OCCUPANCY_CLASS	Hospital	
BUILDING_CODE_1L	130	
BUILDING_CODE2L	131	
DWELLING	No	
AREA_SQMETRE	1421.39	
HEIGHT_FLOORS	4	
HEIGHT_ASSUMPTION	12.192	
GROSS_FlOOR_AREA	5685.54	
MI_AGG	0.375	
MI_TIMBER	0.042	
MI_STEEL	0.026	
MI_CONCRETE	1.645	
MS_AGGREGATE	2132.08	
MS_TIMBER	238.793	
MS_STEEL	147.824	
MS_CONCRETE	9352.72	
MS_TOTAL	11871.4	
SERVICE	1-Health	

***Figure 3.8:** Example of 3D CityGML building models for St. George Parish, Grenada (with attributes).*

3.3.5 3D WebGIS application

The Grenada 3D Material Stock Web Application was developed using ArcGIS API for JavaScript version 4.21 and allows government officials, planners, citizens, as well as people around the world to explore material stocks in Grenada from the 3D perspective and interact with the 3D city models. The application is shared on the following link: https://codepen.io/Lingfei_ye/full/yLogBgM. The code of the application including HTML, CSS, and JavaScript can be viewed at this link: https://codepen.io/Lingfei_ye/pen/yLogBgM. The screenshots of the application are shown in Figures 3.9 and 3.10 below. An information box briefly introducing the application and credits pops up when users first open the application and users can click on “Start” to begin the exploration.



Welcome to Grenada 3D Material Stock Web Application

This is a non-commercial 3D WebGIS application developed for material stock exploration in Grenada. It is developed using **ArcGIS API for JavaScript version 4.21** and allows users to explore material stocks in Grenada from a 3D perspective and interact with the 3D city models (e.g., zooming in or out, viewing material stock information in buildings and road segments, querying material stock statistics by geometry, assessing building material stocks vulnerable to Sea Level Rise, etc.).

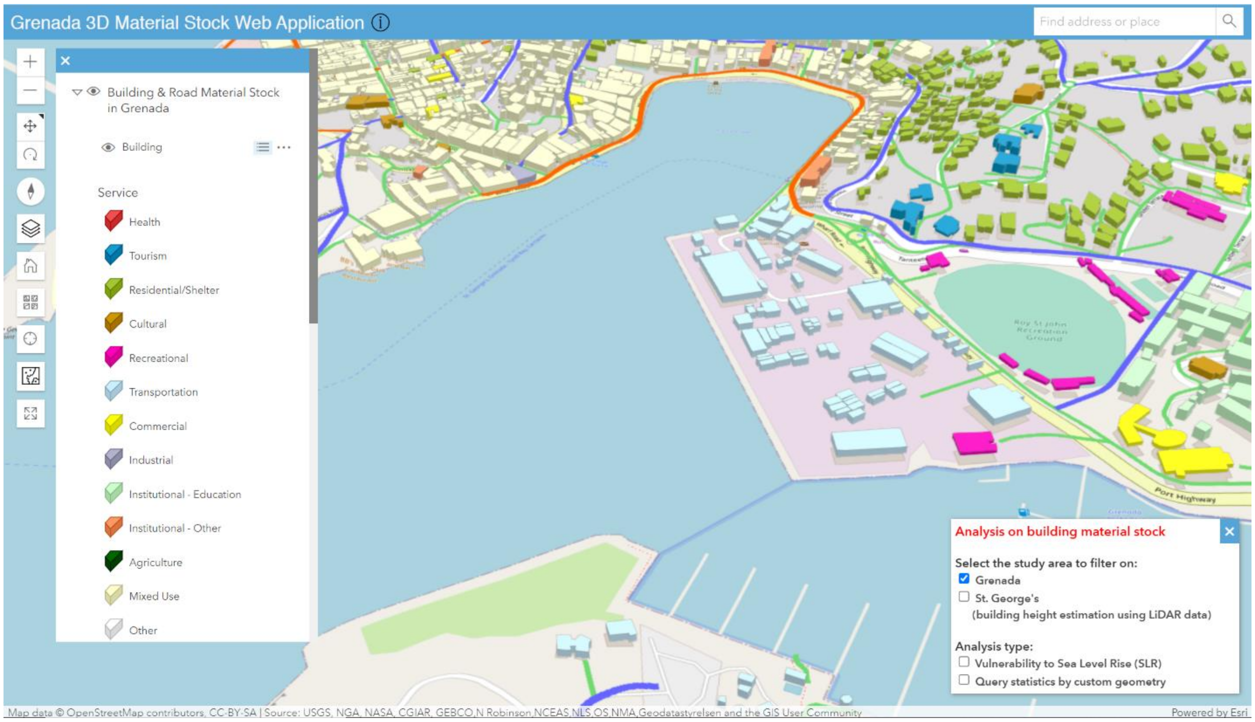
Credits:

The following external libraries and datasets were used in developing this application:

- Building footprints, road network, rivers, transportation ports, and administrative boundaries published on **Caribbean Handbook on Risk Information Management (CHARIM)**. This website also has a set of maps that use these layers.
- Land use & land cover map provided by Ministry of Agriculture, Forestry & Fisheries, Government of Grenada.
- Material stock data developed by **Rob Symmes (2017)**, **Kristen De Kroon (2020)**, and Lingfei Ye (2021).
- Sea Level Rise scenarios developed from **Grenada Digital Elevation Model (DEM)** (for Grenada case) and the Digital Terrain Model (DTM) (for St. George's case) derived from LiDAR data (provided by Land Use Division, Ministry of Agriculture, Government of Grenada)
- UI icons built by Esri for applications **(calcite-ui-icons)**.

Contact: Lingfei Ye (University of Waterloo)

Figure 3.9: *Grenada 3D Material Stock Web Application interface (information box).*



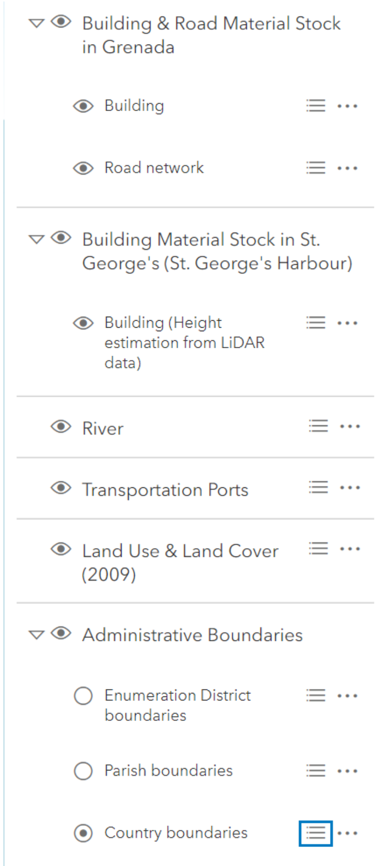
Analysis on building material stock

Select the study area to filter on:
☑ Grenada
☐ St. George's
(building height estimation using LiDAR data)

Analysis type:
☐ Vulnerability to Sea Level Rise (SLR)
☐ Query statistics by custom geometry

Figure 3.10: *Grenada 3D Material Stock Web Application interface.*

The building layer and the road network layer for the main island of Grenada are the default layers shown on the application. Buildings are coloured based on their service types and roads are coloured based on the road hierarchy. The height of each building block represents the building height. Other layers include the building layer for the sample site in St. George’s, river layer, transportation port layer, land use and land cover layer, and administrative boundary layers for Grenada (as shown in Figure 3.11).



- Building & Road Material Stock in Grenada
  - Building
  - Road network
- Building Material Stock in St. George's (St. George's Harbour)
  - Building (Height estimation from LiDAR data)
- River
- Transportation Ports
- Land Use & Land Cover (2009)
- Administrative Boundaries
  - ○ Enumeration District boundaries
  - ○ Parish boundaries
  - ● Country boundaries

Figure 3.11: *Full list of layers on Grenada 3D Material Stock Web Application.*

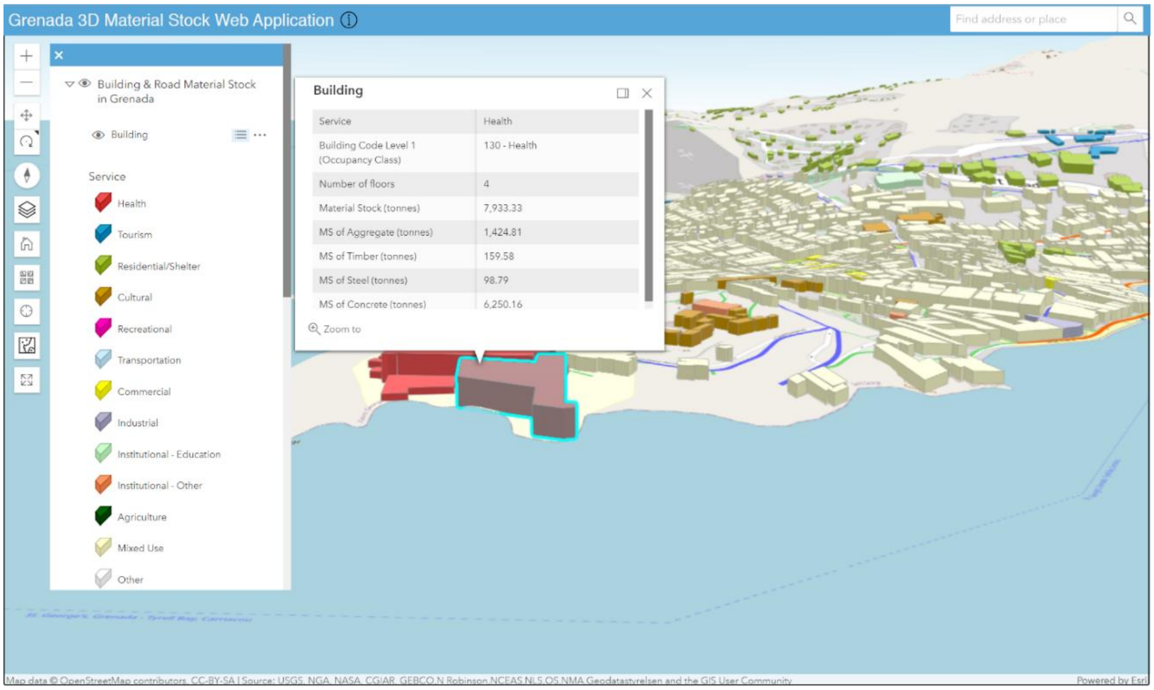
Figure 3.12 provides a screenshot of the application with annotations explaining divisions and widgets in the application. The information icon (#1) is for turning on the information box as shown in Figure 3.9. The #2 division is the layer list and legend division with three actions (i.e., go to the full extent, increase or decrease opacity) on the layer. Several widgets (#3 & #9) for adjusting the view are placed on the left side including Zoom in/out, Pan/Rotate, Reset Orientation, and Full Screen. The #4 button can turn on and off the layer list division, while the #8 button can turn on and off the analysis on building material stock division (#11). The #5 Home widget can lead users back to the default view and the #7 Locate widget and #10 Search widget allows users to go to their current locations or locations they wish. The Basemap Gallery widget (#6) provides users with options to display different basemaps under the layers. When clicking on an individual building or road segment on the map as shown in Figures 3.13 and 3.14, a pop-up appears presenting information on the object, such as the class, size, and material stock information.

Analysis on building material stock

Select the study area to filter on:
☑ Grenada
☐ St. George's
(building height estimation using LiDAR data)

Analysis type:
☐ Vulnerability to Sea Level Rise (SLR)
☐ Query statistics by custom geometry

Figure 3.12: *Grenada 3D Material Stock Web Application interface with annotations.*

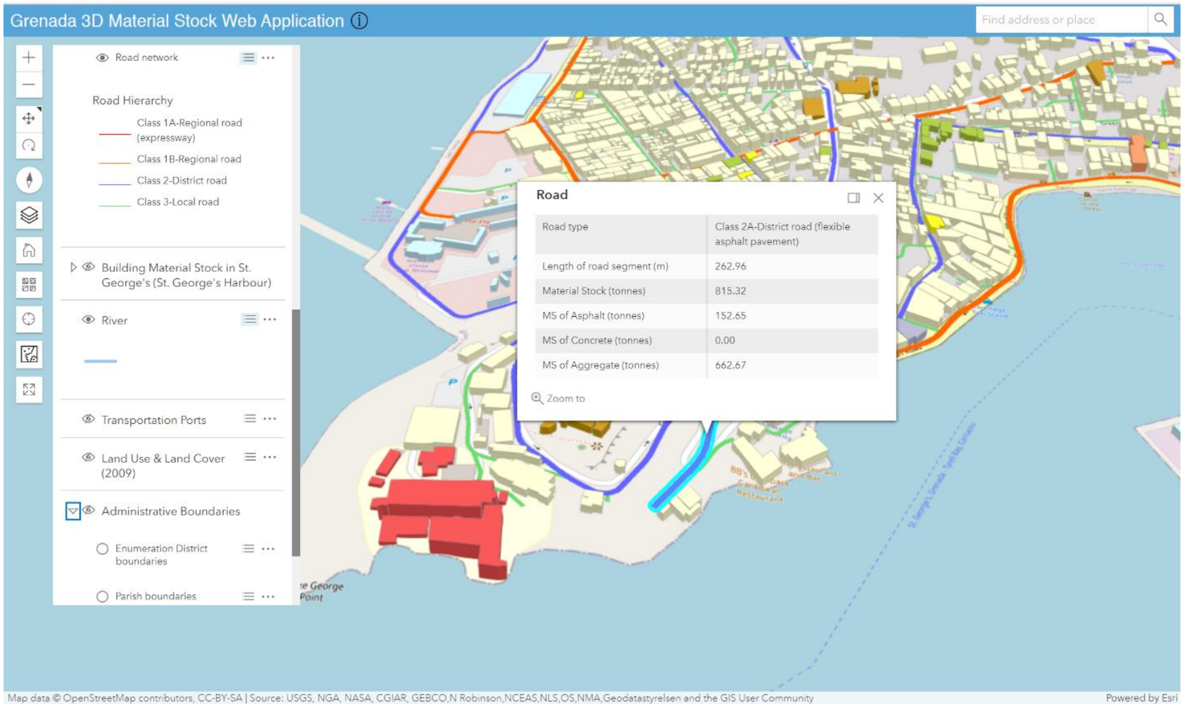


Building

Service	Health
Building Code Level 1 (Occupancy Class)	130 - Health
Number of floors	4
Material Stock (tonnes)	7,933.33
MS of Aggregate (tonnes)	1,424.81
MS of Timber (tonnes)	159.58
MS of Steel (tonnes)	98.79
MS of Concrete (tonnes)	6,250.16

Zoom to

Figure 3.13: *Grenada 3D Material Stock Web Application interface (pop-up for building).*



Road

Road type	Class 2A-District road (flexible asphalt pavement)
Length of road segment (m)	262.96
Material Stock (tonnes)	815.32
MS of Asphalt (tonnes)	152.65
MS of Concrete (tonnes)	0.00
MS of Aggregate (tonnes)	662.67

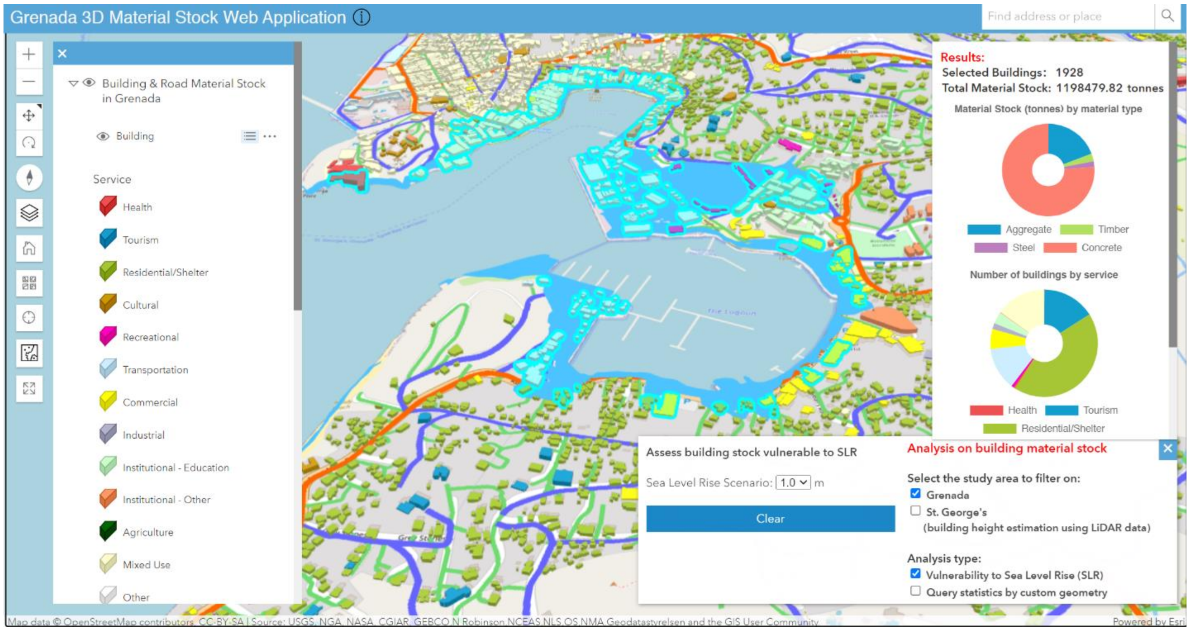
Zoom to

Figure 3.14: *Grenada 3D Material Stock Web Application interface (pop-up for road).*

Two types of analyses on building material stocks were added to the application: sea level rise vulnerability mapping (Figures 3.15 & 3.16) and spatial query by custom geometry (Figure 3.17). Two study areas can be selected using the checkbox; one is the main island of Grenada, and another is the sample site in St. George's (as described in Section 3.2.1). For the Grenada study area, the building heights were based on occupancy classes, while material stock estimates were from previous research by De Kroon (2020). Sea level rise scenarios (1.0 m and 2.0 m) were generated based on a Grenada DEM with 5-meter pixel size. For the St. George's study area, the building footprints were adjusted, and the heights of buildings were derived from LiDAR elevation data as explained in Section 3.2.1.2. Material stocks were recalculated using the LiDAR-derived heights (refer to Section 3.2.1.3) and the sea level rise scenarios (0.25 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m) were generated using DTM created from LiDAR data (refer to Section 2.2.4).

In terms of the sea level rise vulnerability mapping, users can select the scenario using the drop-down box, after which the inundation zone is automatically displayed in the view and the buildings vulnerable to the sea level rise scenario are highlighted. In addition, a related result division appears in the top right corner displaying summary statistics including the total number of vulnerable buildings, the amount of vulnerable building stocks, and two pie charts showing material stocks by materials and service types.

In terms of spatial query by custom geometry, users can easily draw a point, polyline, or polygon on the map and set the buffer size using the slide bar to select buildings. The summarized material stocks statistics of selected buildings are then presented as shown in Figure 3.17.



Results:
Selected Buildings: 1928
Total Material Stock: 1198479.82 tonnes

Assess building stock vulnerable to SLR
Sea Level Rise Scenario: 1.0 m

Analysis on building material stock

Select the study area to filter on:
☑ Grenada
☐ St. George's
(building height estimation using LiDAR data)

Analysis type:
☑ Vulnerability to Sea Level Rise (SLR)
☐ Query statistics by custom geometry

Figure 3.15: *Grenada 3D Material Stock Web Application (sea level rise vulnerability mapping for Grenada).*

Results:
Selected Buildings: 330
Total Material Stock: 222844.00 tonnes

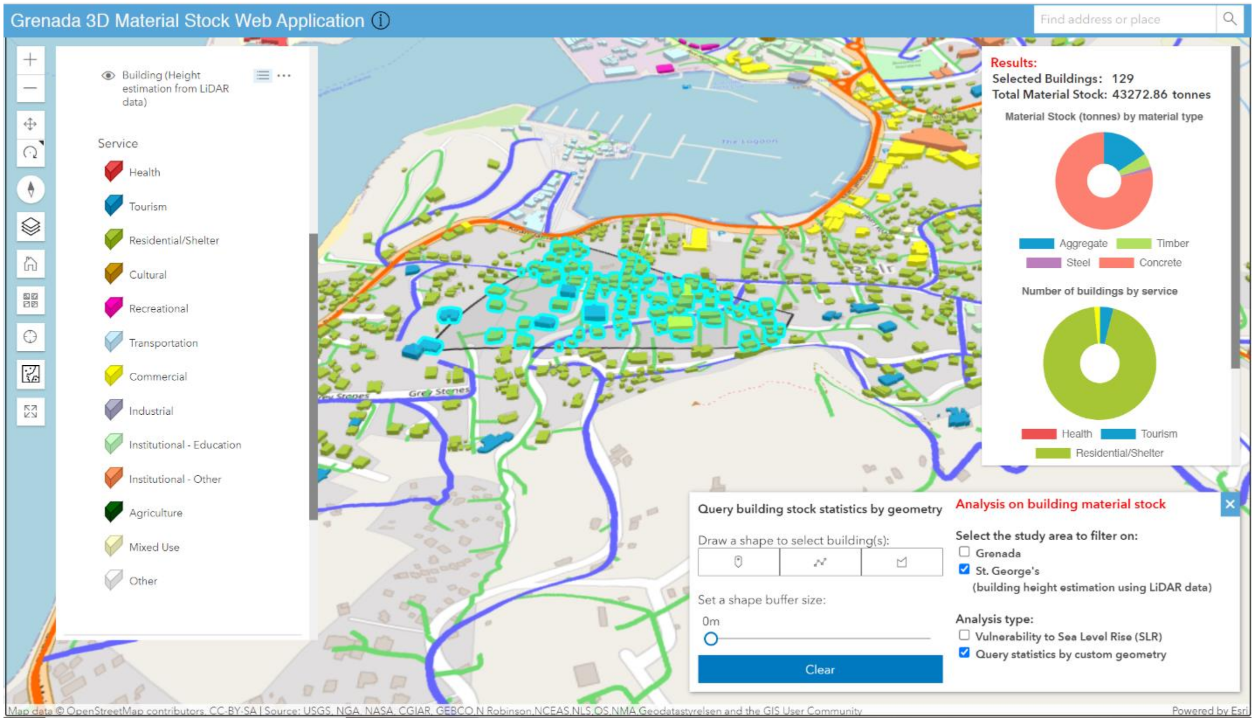
Assess building stock vulnerable to SLR
Sea Level Rise Scenario (St. George's): 1.5 m

Analysis on building material stock

Select the study area to filter on:
☐ Grenada
☑ St. George's
(building height estimation using LiDAR data)

Analysis type:
☑ Vulnerability to Sea Level Rise (SLR)
☐ Query statistics by custom geometry

Figure 3.16: *Grenada 3D Material Stock Web Application (sea level rise vulnerability mapping for sample site in St. George's).*



Results:
Selected Buildings: 129
Total Material Stock: 43272.86 tonnes

Query building stock statistics by geometry

Draw a shape to select building(s):

Set a shape buffer size:
0m

Analysis on building material stock

Select the study area to filter on:
☐ Grenada
☑ St. George's
(building height estimation using LiDAR data)

Analysis type:
☐ Vulnerability to Sea Level Rise (SLR)
☑ Query statistics by custom geometry

Figure 3.17: *Grenada 3D Material Stock Web Application (query statistics by geometry).*

3.4 Discussion

This section discusses the key results from the 3D GIS modelling of building material stocks in Grenada. The effects of utilizing LiDAR data in building height estimation and material stock estimation in the context of small island states are discussed, followed by a discussion of the 3D products (i.e., 3D building models and 3D WebGIS application) of this study. A comparative review of building material stock studies in Grenada are included and limitations of this work and potential future work are also addressed.

3.4.1 Building height estimation using LiDAR data in the context of small island states

In this study, with the lower MAE (mean absolute error) and RMSE (root mean squared error) from the ground truth height, LiDAR-derived building height estimates show higher accuracy than height assumptions based on occupancy classes (i.e., buildings of the same occupancy class share the unified height value) used in previous research. Compared with the LiDAR-derived height estimates, the assumed building heights from De Kroon (2020) based on occupancy classes tend to overestimate building heights and fail to capture the heterogeneity of building heights within the same occupancy class, which is more problematic for urban areas where diverse buildings are concentrated.

Due to limited data availability, current research on small island states usually utilizes classified building datasets with unified height assumptions and assumes uniformity in building dimensional characteristics in each building class. Few previous studies have considered obtaining the actual height of individual buildings using LiDAR elevation data instead of manual on-site surveys. The automatic process of building height estimation using GIS techniques can save considerable manual effort and be applied to large-scale study areas. This study not only explores the viability of using LiDAR data to estimate building heights in the context of small island states, but also demonstrates that LiDAR data can provide more accurate building height estimates and better capture the dimensional characteristics of buildings. These findings are consistent with results of previous studies using LiDAR data to extract building heights in developed study areas (Park & Guldmann, 2019; Wu, Blunden, & Bahaj, 2019).

3.4.2 Material stock estimation using LiDAR-derived building height data in the context of small island states

The accuracy of building height assumptions or estimates affects the accuracy of the physical size estimation and material stock estimation. Accurate material stock estimation is essential for efficiently managing materials stocked within a socio-economic system, controlling material inflows and outflows, and enhancing material reuse and recovery. This is especially important for small island states which are limited in natural resources and highly depend on material imports. The building height accuracy assessment shows that building heights estimated from LiDAR elevation data can improve the building height assumptions adopted in previous material stock studies in Grenada; therefore, LiDAR-derived height estimates were used to recalculate accumulated material stocks in an urban area of Grenada.

The results show that using height assumptions from the previous research (De Kroon, 2020) resulted in 57.08 kilo tonnes of overestimation in building stock estimates (about 4.8% of the total stocks) compared to using LiDAR-derived heights. Since most of buildings in Grenada are concrete-intensive, it is not surprising that the most discrepancy in stock estimates could be observed in concrete, which accounted for over 80% of the total stock difference.

Among all service types, the largest sums of differences were observed in residential buildings, followed by commercial and mixed use buildings. The most significant variation in each building occurred in health service buildings, followed by industrial, commercial, and institutional buildings. This is because residential and mixed use buildings tend to have lower numbers of floors and smaller footprint area compared with health, industrial, or institutional buildings, which leads to lower differences of stock estimates in a single building. However, the numbers of residential and mixed use buildings are the highest among all service types; therefore, the sums of stock differences are the highest. Health, industrial, and institutional buildings tend to have larger footprint area among all buildings, resulting in higher errors in individual buildings.

3.4.3 3D building model and 3D WebGIS application

This study developed the 3D building models and 3D WebGIS application for Grenada to integrate material stocks with 3D city models. The 3D building models are in CityGML format which represents both semantics and geometry of the models and helps improve data integration, communication, and interoperability (Gröger & Plümer, 2012). Including material stock, service type, occupancy class, building code, height assumption, and other attributes, the 3D building models for Grenada can be easily applied to future urban planning use cases, such as visualization for navigation, urban information communication, vulnerability assessment, material stock management, carbon emission assessment, and energy demand assessment.

Because of the complexity and large size of GIS data and 3D city models, clients without technical knowledge and specialized software may find it challenging to access and understand the data. Therefore, it is important to develop a user-friendly interface to allow for easy interaction between practitioners with 3D models and datasets. This study developed a 3D WebGIS application based on ArcGIS API for JavaScript, which visualizes the status of in-use material stocks in Grenada from a 3D perspective. Users can navigate through the 3D city model of Grenada by utilizing simple operations (e.g., drag, rotate, click, etc.). Related information can be viewed, including the structure's physical size, the service type, and different materials stocked in the structure. Users can also query material stock statistics of selected buildings by drawing shapes on the map and obtain summary statistics of vulnerable material stocks by selecting sea level rise scenarios.

Integrating material stocks in 3D city models and the WebGIS application explores a new application of material stocks and provides a novel way to present material stock estimates instead of using static maps or tabular statistics outputs. This 3D WebGIS application allows policy makers and practitioners to visually assess material stocks from a 3D perspective and enhance their understanding of in-use material stocks. In addition, this application enables the general public to get close to 3D city models and material stocks and encourages public participation in urban planning.

3.4.4 Comparative review of material stock studies in Grenada

There have been three studies (including this study) focusing on building material stock accounting and analysis in Grenada (De Kroon, 2020; Symmes et al., 2019). The comparison of the three studies is summarized in Table 3.5. All three studies used GIS-based bottom-up approaches to quantify and map the in-use building material stocks in Grenada. Symmes et al. (2019) developed the first set of building material intensity coefficients and classified buildings into different occupancy classes. Each occupancy class was assumed to be homogeneous sharing the same material intensity typology and the same number of floors. Building stocks were then calculated by multiplying material intensity by the gross floor area (GFA = average building height × footprint area). Symmes et al. (2019) assigned each occupancy class an average building height (the number of floors) based on composite image interpretations without accuracy assessment. Therefore, De Kroon (2020) conducted fieldwork and assessed the accuracy of building height assumptions and associated occupancy classes used by Symmes et al. (2019). Based on the accuracy assessment results, De Kroon (2020) modified the building classification throughout Grenada and recalculate the building stocks using the same equation as Symmes et al. (2019). Although De Kroon (2020) tried to improve the height assumptions from a national level based on fieldwork observations, the heterogeneity among buildings of same class and the vertical assemblies have not been captured. This study aimed at addressing the assumption in previous studies that each occupancy classes has the same number of floors and integrated LiDAR data with footprint data to obtain the actual building height of individual building. The building stocks were recalculated by multiplying the material intensity by the volume of building (calculated from the floor area and building height).

Table 3.5. *Comparison of the three building material stock studies in Grenada*

	Symmes et al. (2019)	De Kroon (2020)	Ye (2022)
Material stock accounting approach	• GIS-based bottom-up approach • Physical size of buildings: Gross Floor Area (GFA) • Building height: assumed same number of floors in each building occupancy class	• GIS-based bottom-up approach • Physical size of buildings: Gross Floor Area (GFA) • Building height: assumed same number of floors in each building occupancy class	• GIS-based bottom-up approach • Physical size of buildings: Gross Volume (GV) • Building height: height estimates of individual buildings using LiDAR data
Focus and Scope	• Develop building occupancy classes and material intensity typologies • Estimate building material stocks in Grenada	• Conduct fieldwork to assess the accuracy of height assumptions and building classification in Symmes et al. (2019) • Recalculate building material stocks	• Integrate LiDAR data with footprint data to estimate building heights for individual buildings • Conduct accuracy assessment of building heights and investigate the differences in building stock estimates

	• Conduct the material flow analysis of construction materials • Estimate potential material stock loss due to hurricanes and sea level rise	• Link building stocks to services and assess the future growth of material stocks	• Develop 3D building models and a WebGIS application to visualize the material stock account of Grenada
Total material stocks in Grenada	• Building stocks: 11,959 kilo tonnes, 112 t/capita	• Building stocks: 14,012 kilo tonnes, 132 t/capita	• Building stocks: 13,372 kilo tonnes, 125 t/capita • Road stocks: 4,375 kilo tonnes, 41 t/capita • Total stocks: 17,747 kilo tonnes, 166 t/capita
Key messages & deliverables	• First building stock account of Grenada showing the quantity and spatial distribution of building stocks • Sensitivity analysis shows that accuracy of the building classification and building height assumptions can have huge impacts on the accuracy of final stock estimates • Fieldwork validation is required to improve the classification system and adjust the height assumption assigned to each occupancy class	• Updated material stock account of Grenada including information on the quantity, spatial distribution, and provided services of building material stocks • Significant variation of building heights exists even within the same occupancy class • Height assumptions in the GFA approach can result in large underestimation in material stocks of residential buildings	• First 3D building models with material stock information and first 3D material stock web application of Grenada • LiDAR-derived building heights are closer to true building heights and can better capture the heterogeneity among buildings • Results of the sample site show that using the GFA in stock accounting can result in overestimation in total building stocks compared to using the GV • Largest sum of material stock differences can be observed in residential, commercial, mixed use, and institutional buildings • The highest discrepancy of stock estimates in single building can be observed in the health sector, followed by industrial,

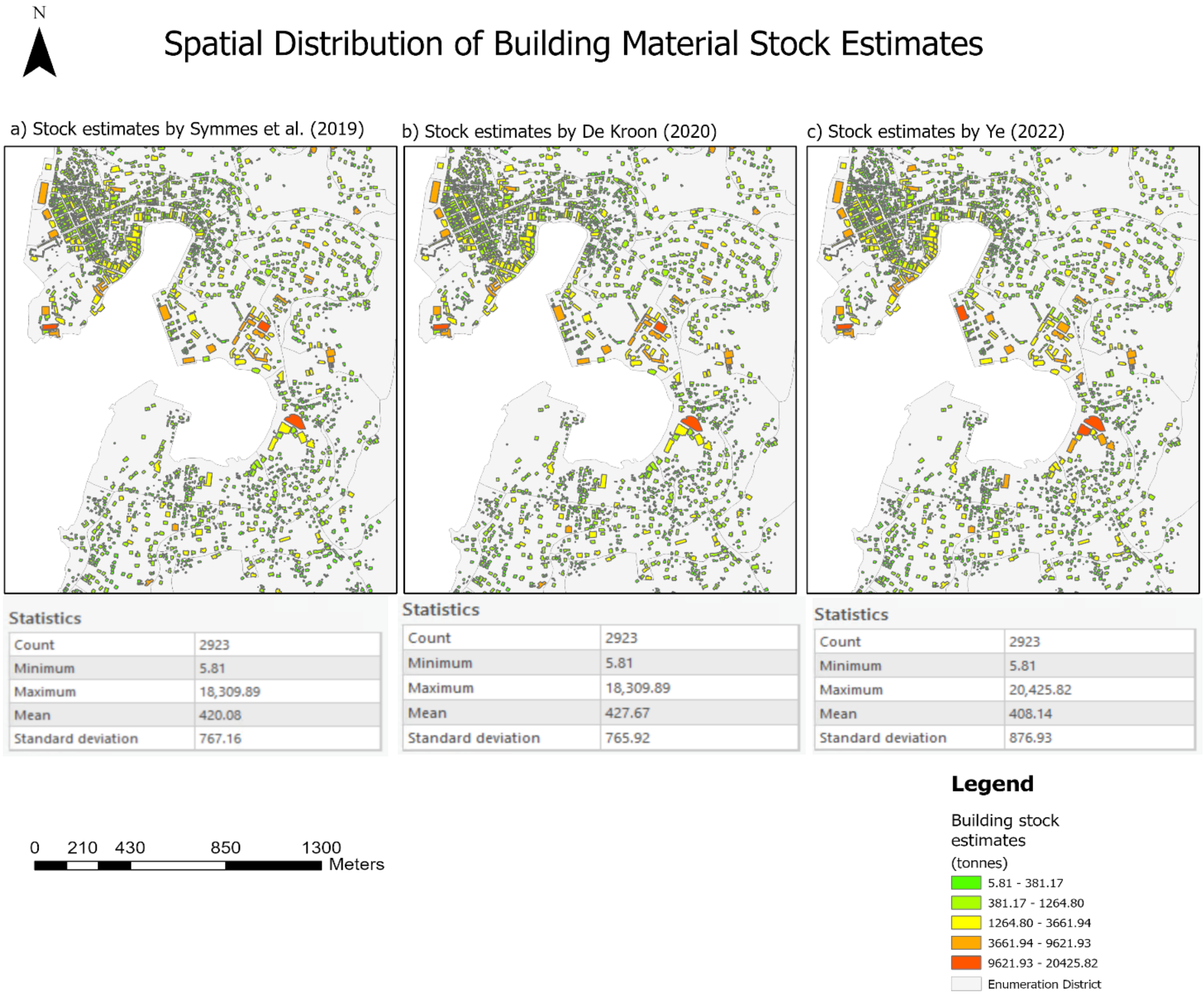
			commercial, and institutional sectors, which tend to have buildings with larger footprint area
Advantages & disadvantages of each approach	• GIS-based bottom-up material stock accounting approach can effectively quantify and map the material stocks • Inaccurate building classification and height estimates can cause significant uncertainties to results • The quality of the GIS data can also affect the accuracy of the material stock account	• Building stock accounting using the GFA is a good overall approach if the numbers of floors are relatively uniform within the same building occupancy class • Building stock accounting using the GFA can produce relatively good building stock estimates on a large spatial scale (e.g., national scale) and show the overall spatial distribution • The uncertainties and errors in the building classification and height assumption can affect the accuracy of material stock account and may have significant impacts on outflow waste analysis and management	• Building stock accounting using the LiDAR-derived GV is feasible even in study areas with complicated built environments and diverse buildings concentrated • Building stock accounting using the LiDAR-derived GV can produce accurate and spatially highly resolved stock estimates with less fieldwork and labour cost • Detailed and practicable stock information aids in site-specific analysis and assessment • LiDAR data are expensive, hard to access, and often not available for small island states • Dealing with LiDAR data require fast and high-memory computing environment and is time-consuming
Potential applications	• Study area has spatial building footprint data available, but no availability of LiDAR data, cadaster data or detailed information on building heights • Applications where buildings of the same occupancy class are assumed to have homogenous building heights		• Study areas has both spatial building footprint data and LiDAR data • Accounts for significant variation of building heights exists in the same occupancy class

	• Regional or country-level analyses (e.g., large study areas). Obtaining a rough estimate of material stocks for an entire island scale.		• The goal is to detect the detailed state of building material stocks in a specific study area
Potential questions to address	• What is the mass and composition of in-use building material stocks in the entire country? • Where are the concentrations of building stocks in the country? • What is the amount of building material stocks at risk under different disaster or sea level rise scenarios and where are vulnerable areas?	• What are the units of different societal services provided by in-use building material stocks? • What are the driving factors behind the concentrations of building material stocks?	• What is the current state of building material stocks in the city or local site? • How are building stocks being used efficiently at the local area level? • Are existing building stocks sufficient for supporting critical societal services? • How can existing material stocks be used to support more societal services? • What is the amount of potential waste from current in-use building stocks and where are they located?

Results of De Kroon (2020) illustrated that heights of buildings with different numbers of floors were not overlapped so it is reasonably to apply height assumptions and gross floor area to building stock accounting in Grenada. Comparing the height assumptions used by Symmes et al. (2019) with the fieldwork observations, De Kroon (2020) observed the underestimation of numbers of floors in 32% of buildings surveyed and overestimation in 14% of buildings. De Kroon (2020) found that 55% of building samples were not classified correctly in the classification system used by Symmes et al. (2019). The major misclassification (32%) occurred in residential buildings and between rural-area single-family dwellings (one-storey buildings) and residential-area single-family dwellings (two-storey buildings). Therefore, De Kroon (2020) modified the building classification by converting 32% of rural-area single-family dwellings to residential-area single-family dwellings throughout Grenada.

Results of this study demonstrate that LiDAR-derived height estimates were closer to the true building heights compared with height assumptions in Symmes et al. (2019) and De Kroon (2020) and can properly represent the heterogeneity among buildings. De Kroon (2020) found that heights of residential buildings tended to be underestimated in previous height assumptions by Symmes et al. (2019), which resulted in underestimation of total building stocks. However, this study finds that in the sample site, heights of residential buildings were overestimated in previous height assumptions by De Kroon (2020) and Symmes et al. (2019). Comparing the stock estimates in the sample site calculated by De Kroon (2020) and this study, using the class-based height assumptions resulted in about 57.08 kilo tonnes of overestimation (about 4.8%) compared to using LiDAR-derived heights. When applying this to the whole island, there would be an overall difference of 640 kilo tonnes (7 t/capita). Residential, commercial, mixed use, and institutional building stocks resulted in the largest sum of differences. The highest discrepancy of stock estimates in single building was observed in the health sector, followed by industrial, commercial, and institutional sectors, which tend to have buildings with larger footprint area. Comparing three studies' total building stock estimates for Grenada (as shown in Table 3.5), it can be seen that De Kroon (2020) had the highest estimates (14,012 kilo tonnes, 132 t/capita) followed by this study (13,372 kilo tonnes, 125 t/capita) and Symmes et al. (2019) (11,959 kilo tonnes, 112 t/capita). The difference between this study and Symmes et al. (2019) was 1,418 kilo tonnes (7 t/capita).

Comparing three studies' building stock estimates in the sample site and the spatial distribution of building stocks (as shown in Figure 3.18), it can be seen that using LiDAR-derived heights in stock estimation resulted in higher standard deviations, which indicates that building stock estimates using LiDAR-derived heights can better capture the deviations among buildings. Since De Kroon (2020) only modified the residential building classification and the footprint area of residential buildings is relatively small, there is no obvious changes of stock estimates in individual buildings and the spatial distribution of stock estimates is similar with results of Symmes et al. (2019). However, building stock estimates using LiDAR-derived heights in this study show different distribution from the other two studies. Buildings with larger footprint areas show distinct differences in stock estimates and stock estimates of mixed use buildings which cluster in the town center (on the west of the Carenage) show more heterogeneity.



Statistics

Count	2923
Minimum	5.81
Maximum	18,309.89
Mean	420.08
Standard deviation	767.16

Statistics

Count	2923
Minimum	5.81
Maximum	18,309.89
Mean	427.67
Standard deviation	765.92

Statistics

Count	2923
Minimum	5.81
Maximum	20,425.82
Mean	408.14
Standard deviation	876.93

Figure 3.18: *Comparison of building material stock estimates in three studies in St. George's, Grenada (Symmes et al. (2019), De Kroon (2020), and this study)*

Comparing the methodology used in three studies, the main difference is how to measure the physical size of the building. Previous two studies (De Kroon, 2020; Symmes et al., 2019) used the gross floor area (GFA) in building stock calculation, which has shown reasonable confidence in building stock estimation in Grenada. Building stock accounting using GFA is suitable for areas with high homogeneity in building heights and can effectively quantify and map the building stocks on a large spatial scale (e.g., national scale). Using GFA inherently causes assumptions in building heights, which brings errors in material stock estimates, and the most accurate way is to conduct fieldwork or use high-quality cadasters to obtain the accurate height of the individual building. However, it is not efficient to conduct fieldwork on each building and cadasters are often difficult to access and often not available in small island states. Therefore, to improve height estimation and material stock estimation, the application of highly resolved 3D LiDAR data could be a possible solution, which allows for the accurate calculation of building gross volume (GV) and the highly detailed estimation of building stocks with regard to spatial resolution. Building stock accounting using LiDAR-derived GV is feasible even in study areas with complicated built environments and diverse buildings concentrated and can produce accurate stock estimates of individual buildings. Relatively accurate and spatially high-resolved building stock estimates enable further analysis (e.g., energy and resource efficiency assessment, demolition waste and emission estimation, reuse and recycling potential estimation, and infrastructure vulnerability assessment) at a local scale or even at the building level. Improved material stock accounts can provide finer insights for urban planning, waste management, disaster management, and civil infrastructure developments, which are important for small island states where rapid urbanization is ongoing with more buildings and infrastructure being built but the reuse and recycling rate is relatively low. In addition, small island states are highly vulnerable to climate change and do not have enough well-developed infrastructure which limit the capacity to mitigate climate impacts and necessitate the sustainable and efficient material management and robust infrastructure development (Nurse et al., 2001; UNOPS & University of Oxford, 2020).

LiDAR data are expensive and often not available for small island states. Advanced and high-memory computing environment and long processing time are also required dealing with LiDAR data. Therefore, material stock accounting using LiDAR-derived GV may not be feasible for many small island states or large study areas. Instead of relying on a single method, it is possible to integrate different methods for material stock accounting, which allow for the investigation of the material stock account at different scales or within different contexts. Having a suite of methods available aids small islands states in their preparedness for environmental hazards and achieving more comprehensive and reliable development plans.

It is recommended for the investment in LiDAR data or other accurate information. This study showcases the feasibility and benefits of using LiDAR data in building height estimation, material stock accounting, 3D building model and web application development. To aid urban planning and resource management, more applications of LiDAR data can be explored, such as building edge extraction, building rooftop slope extraction, digital elevation models or digital terrain models development, land use/cover detection, optimal solar panel positioning, 3D vegetation structure modelling, and other applications in different domains.

3.4.5 Limitations and future work

As mentioned in the Section 3.2.1.2.1, inconsistency exists between LiDAR data and building footprint data for Grenada. LiDAR data are more up-to-date and overlapped better with the orthophoto. The deviations between LiDAR building points and building footprints result in difficulties in extracting building points within footprints and deriving height data to footprints. In this study, the footprint data was manually adjusted to match two datasets; however, the dislocation of two datasets still exists, which may cause some important height data missing within the footprint and affect the height estimate. Manual adjustments are feasible for a small study area, but when it comes to larger regions, such as the entire country, manual adjustment becomes time-consuming and may introduce significant human errors. A key recommendation from this research that building footprint data for Grenada should be kept up to date, including adding new buildings, removing non-existent buildings after 2014 and rechecking the spatial positions of footprints.

Another limitation related to the footprint data for Grenada is that the footprints do not provide details of building roofs and assume all building roofs to be simple flat tops ignoring height variations. Therefore, only one height value could be assigned for one building. The average height of LiDAR building points was finally adopted to represent the height of the rooftop midpoint in this study because of the relatively higher accuracy. Ignoring the height variation of the roof surface would result in inaccurate computed height and gross volume, which may affect further analysis utilizing these measures, such as the material stock estimation. In addition, losing the rooftop details limits the generation of 3D building models. In this study, only LoD1 (Levels of Detail) building models could be generated and buildings were represented as simple solid blocks. 3D building models with lower levels of details would limit the application of 3D models. Some use cases, such as solar irradiation estimation, shadow cast estimation, 3D cadaster, and energy demand assessment would become difficult to accomplish without detailed and accurate 3D building models. If building footprints with detailed roof shape and orientation information are available in the future, the 3D building models and the 3D Web application for Grenada will be improved and prepared for various 3D city model use cases.

Since the 3D WebGIS application is developed using the ArcGIS API for JavaScript and uses the feature layers stored on the ArcGIS server, all functionalities are implemented by the data services hosted on the ArcGIS Platform. The ArcGIS API provides users with efficient and seamless interfaces to the ArcGIS platform and allows users to build comprehensive web apps easily using packed modules. However, there are some limitations related to the API and data services; for example, the query operation on server-side layers has lower processing speed and weaker responsiveness compared with the query on client-side layers. Server-side layers refer to feature layers stored on the server and fetch required features when being requested, while client-side layers refer to feature layers stored on the client-side and fetch all features when clients load the app (ESRI, 2021c). In this study, the “spatial query by custom geometry” function in the app queries features by client-side geometry layer drawn by clients; therefore, it can run at a fast speed even when querying all features on the island. The “sea level rise vulnerability mapping” function queries vulnerable features by the geometry of inundation area layers which are stored as server-side feature layers. The running speed becomes slow and the maximum number of returned features from the query is 2,000, which causes troubles when changing the study area to the whole country. To solve this problem, this study queried features first using Intersect tool in ArcGIS software and then applied the results to the feature layer. This method saves running time and overcomes the upper limit problem; however, it restricts the flexibility of the app. When inundation area layers are updated, instead of automatically re-querying features through running the code, the query operations in the ArcGIS software must be performed again and all results must be updated in the app.

High-density LiDAR point clouds demand large storage space and considerable computer processing capacity. Given the limited processing power in this study, building height estimation using LiDAR data only focused on one of the built-up urban areas in Grenada. More studies are required to test the feasibility and performance of the methodology in other study areas including rural areas and other built-up areas with buildings of different service types. In the future, if high-quality data and advanced computing environment are available, the integration between different data sources will be improved and a comprehensive and accurate national material stock account for Grenada can be produced. More applications of material stocks and 3D city models can be explored helping policy makers and planners improve resource management and city planning in the context of small island states.

Chapter 4

Thesis Conclusions

4.1 Key Findings

This thesis focuses on in-use material stock accounting on a small island state, Grenada using a geospatial approach. The general goal of this project is to improve the current material stock accounting and modelling framework for Grenada as well as small island states. Manuscript 1 (Chapter 2) focuses on estimating total road material stocks on Grenanda and aims at developing a methodological approach to estimate and analyze in-use road stocks. Manuscript 2 (Chapter 3) focuses on the building material stock and seeks to apply 3D LiDAR point clouds to building stock estimation and develop a web-based product that integrates 3D city models and material stock estimates. The key findings of this research are summarized in the following sections.

4.1.1 GIS modelling of road material stock

The first study developed a GIS-based bottom-up approach to model in-use road material stocks in Grenada and assessed the vulnerability of road stocks to potential sea level rise scenarios. The road stock accounting yielded a total stock of 4,375 kilo tonnes (40.96 t/capita) which occupied a large share (24%) of total material stocks in Grenada. Aggregates stocked within the road network account for the largest proportion of stocks and contributed to 55% of total aggregate stocks. The considerable amount of road stocks indicates the important role of materials stocked in non-building infrastructure in the context of small island states. A comprehensive and accurate account of material stocks for small island states requires the consideration of both building and non-building structures, including roads, ports, dams or other structures. Compared with developed countries, Grenada has a relatively low proportion of road stocks and fewer asphalt paving roads which may result from the geographic and climate characteristics, investment structure, and technology constraints.

The spatial distribution maps of road stocks were able to identify a heavy accumulation of road stocks in low-lying coastal areas, especially in the major cities/towns, and in the southwestern part of the island (i.e., St. George Parish). These are the areas where the majority of population reside, critical infrastructures are concentrated, and most economic activities occur. Road stocks accumulated along coastal areas are especially susceptible to extreme weather events and sea level rise. The results of this study suggest that a sea level rise of 1.5 m or above can potentially inundate the majority of roads along the St. George's Harbor and over 18,187 tonnes of road stocks in the St. George's Harbor will be at risk under a 2.0 m sea level rise scenario. If the government does not implement any adaptation plans or coastal protection measures, when the global mean sea level rises by 1.0 m or even 2.0 m by the end of this century, most of the road stocks along the coastline will be flooded.

4.1.2 3D GIS modelling of building material stock

The second study modelled the in-use building material stock from a 3D perspective by applying LiDAR data to obtain accurate building heights and to improve estimates of material stocks. The results show that combining GIS footprint data with LiDAR elevation data could effectively derive the accurate building height for each building, and LiDAR-derived height estimates could properly represent the heterogeneity among buildings. With more accurate building heights available, original material stock estimates from the previous study in Grenada (De Kroon, 2020) can be significantly improved by addressing the assumption that buildings of the same occupancy class share the same assumed height. The study for the sample site of Grenada (St. George's) shows that using height assumptions from the previous research (De Kroon, 2020) resulted in 57.08 kilo tonnes of overestimation (about 4.8%) in building stock estimates compared to using LiDAR-derived heights. When applying this percentage of overestimation to the whole island, there would be an overall difference of 640 kilo tonnes (7 t/capita). Buildings of the top four service types (i.e., residential, commercial, mixed use, and institutional) resulted in the largest sum of errors. The most discrepancies in stock estimates occurred in the town center (on the west of the Carenage) where mixed use buildings clustered. The comparative review indicates that building stock accounting using LiDAR-derived building gross volume (GV) is useful when studying complicated built environments with diverse buildings concentrated and can produce relatively accurate and spatially highly resolved stock estimates of individual buildings. An accurate and spatially high-resolved material stock account allows for more resource and energy analyses at different spatial scales and aids in the city's or island's urban planning, resource management, disaster management, and sustainable development.

In addition, 3D building models for Grenada in CityGML format were created and a 3D WebGIS application was developed based on Grenada material stock geodatabase in order to investigate material stocks from a 3D perspective and link material stocks to 3D city models. 3D building models for Grenada are in a popular international city model format and include both semantics and geometry information, allowing future applications in urban planning and data exchange or interactivity. Attributes including the building height assumption, use type, occupancy class, building code, footprint area, material intensity coefficient, material stock, service type, and other properties are also stored in the 3D models. The 3D WebGIS application was developed using the ArcGIS API for JavaScript version 4.21 and is shared on https://codepen.io/Lingfei_ye/full/yLogBgM. It can be embedded in other websites and allow the public to easily access the 3D city model of Grenada and view material stock information from a new perspective. The web application provides many basic widgets and functions for users to navigate the map, adjust the view, change the basemap, and investigate material stocks in each building or road segment. Users can also query material stock statistics by drawing custom geometry to select buildings and can view the statistics of vulnerable building stocks under different sea level rise scenarios.

4.2 Research Contributions

This thesis research contributes to current analyses and applications of material stocks in Grenada as well as other small island states by providing both methodological and practical insights. In terms of methodological contributions, this research developed a new material stock accounting framework for Grenada considering in-use materials stocked within the road network and building structures. Due to the limitation in data availability and data quality, small island states often face challenges and uncertainties in material stock accounting and analysis. This was the first research investigating GIS-based bottom-up road stock accounting in the context of small island states, which provides a fundamental methodological framework that can be applied in other small island states. This research also functions as an exploratory study showcasing the feasibility, uncertainty, and limitation of non-building material stock analysis in the small island states context. Moreover, this research explored the use of high-resolution LiDAR data in building height estimation and building material stock estimation in the small island states context and developed a new methodological approach of building stock accounting which can be further developed in future research on small island states. Finally, the results of this research can provide a foundation for future research on the function of in-use material stocks in a socio-economic system and the relationship of material stocks with economic growth, energy efficiency, and carbon emissions.

In terms of practical contributions, this research updated Grenada's current database on material stocks by including road material stock estimates and improving existing building stock estimates. The first interactive 3D web visualization application for Grenada was developed based on the material stock database and is accessible to policy makers, practitioners, and the public. This publicly accessible web application can contribute to the achievement of the United Nations Sustainable Development Goals (SDGs), especially Goal 11.3 of "enhancing inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries" (UN, 2021, p. 12), and Goal 13.3 calling to "improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning" (UN, 2021, p. 15). The findings of this research and the 3D web product provide Grenada policy makers with insights into the current status of material stocks and existing vulnerability within Grenada's built environment. With a better understanding of the material stock account, policy makers can develop novel strategies to enhance cities' or country's resilience and adaptive capacity to climate change, and improve sustainable development planning and resource reuse and recycling.

4.3 Recommendations

This section reflects on the results and limitations and provides some general recommendations for policy makers and practitioners on future material stock (MS) modelling, analysis, management, and protection.

First, current in-use material stock account for Grenada could be improved in several aspects. An accurate and comprehensive material stock account is important for small island states to understand the status of material stock accumulation within the island and better manage material flow, including material import, reuse, recycle, and deposal. The sustainable management of natural resources is important for achieving the Sustainable Development Goals (SDGs), specifically, Goal 8 (Promote sustained, inclusive and sustainable economic growth), Goal 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), and Goal 12 (Ensure sustainable consumption and production patterns; UN, 2021). The results of this study prove that non-building infrastructure is an important contributor to material stock accumulation in small island states; however, the current material stock account of Grenada only takes building and road stocks into consideration. Other civil infrastructures, such as ports, dams, and utility infrastructure are not included. Previous research has demonstrated that small island states heavily depend on their ports for material imports and exports and stocks in port infrastructure should not be neglected (Tanikawa et al., 2015; Noll et al., 2019; Verschuur, Koks, & Hall, 2021). Therefore, it is necessary to expand the scope of the material stock account. In terms of the building infrastructure, it is recommended to utilize LiDAR data in future building height estimation and material stock estimation. This study has showcased the high accuracy of LiDAR-derived products and provided a methodological framework applying LiDAR data to material stock accounting. Future projects can improve current methodology by exploring more study areas and create an improved building material stock account for the entire country.

Second, the material stock database should be updated to better capture the latest condition of material stock accumulation in the main island, Carriacou, and Petite Martinique of Grenada. In recent years, Grenada has experienced fast growth and expansion in tourism, education, and construction. The changes of in-use material stocks could not be ignored. Thus, the latest data of infrastructure are the key to estimate the accurate material stock amount and show the distribution. In addition, the road classification system and material stock typologies used in road stock accounting should be validated via on-site survey and adjusted to improve the accuracy of material stock estimation. Over years, the road network in Grenada has developed rapidly and the old road classification systems used by governmental agencies sometimes fail to reflect the real condition of roads in Grenada. It is also recommended for the government of Grenada to revise, update, and standardize the current road classification system and nomenclature, which could help better reflect the reality of current conditions and promote inter-departmental cooperation.

Third, vulnerability mapping and capacity assessment regarding material stock should be conducted and enhanced with high-resolution data. Although various vulnerability and hazard mapping have been executed for Grenada, focused analysis of the vulnerability of material stocks to climate change has seldom been compiled. Assess the vulnerability of coastal areas and build resilience is one of the principal objectives of the ICZM policy. Accurate vulnerability analysis could inform the early warning system and enhance future preparedness and decision making in mitigating climate impacts on the island. The vulnerability or risk map of material stock could showcase the amount as well as the location of vulnerable stocks and predict the stocks that will be impacted by climate change or extreme weather events. This study could function as exploratory research to utilize high-resolution LiDAR data in mapping material stock vulnerability to sea level rise. Future accurate vulnerability assessment could expand the scope to the entire island.

Fourth, current material stock account could be used in construction and demolition (C&D) waste estimation and management. Massive material stock accumulation within the socio-ecosystem is followed by massive C&D waste. C&D waste could have high recycling potentials if they are properly managed. Otherwise, massive C&D waste may be discarded back to nature, producing high stress to the living environment, harming the natural environment, and losing its economic value (Fu et al., 2021; Miatto et al., 2019). According to Wiedenhofer et al. (2021), from 1950 to 2015, global end-of-life outflows increased from 0.22 Gt/year to 16 Gt/year by 72-fold and it is expected that in 2028, end-of-life outflows will reach about 22 Gt/year. Dramatically increased end-of-life waste highlights the need to improve the reuse, repair, and recycling of C&D waste and transform the socio-economic system from resource-intensive to material- and energy-efficient (Wiedenhofer et al., 2021). Grenada's material stock account developed by previous studies and this study could be the starting point of estimating potential C&D waste; for example, Miatto et al. (2019) integrated the total stock and expected lifespan to estimate potential demolition waste in Padua. Zheng et al. (2017) estimated the C&D waste in China using the C&D waste production rates and the weight of materials per C&D area. The calculation of C&D waste requires a detailed investigation of construction technologies and a deep understanding of construction lifespan. The standard code of construction waste and support from technical agencies are essential.

Fifth, sustainable maintenance and protection of material stocks are necessary for building Grenada's sustainable and resilient socio-ecosystem. The results of this study have showcased how vulnerable the coastal road stocks are. In addition, large numbers of roads in Grenada lack maintenance. Ruts, cracks, and Potholes are common especially in rigid concrete roads and the widths of roads are relatively narrow and fluctuate dramatically. The carriage width of a road section could range from 3 m to 10.8 m (MOT, 2019). Road rehabilitation projects have been undertaken in recent years. It is recommended to enforce standards for construction incorporating the impacts of climate change and continue road rehabilitation and upgrade projects to improve traffic flow and safety. Coastal protection measures (e.g., sea wall, rock armour, coastal setback regulations, infrastructure reallocation, etc.) should also be implemented to safeguard road stocks from sea level rise and storm surges. More resilient road infrastructure can ensure equal access to critical services, support the country's economy, reduce demolition waste, protect the natural environment, and promote disaster relief.

Finally, 3D city models and 3D WebGIS applications have been increasingly employed in urban planning and many other domains. As the GIS techniques have developed, 3D city models and web apps have proven their utility for various management, analysis, interaction, and simulation functionalities beyond simple visualization. With LiDAR data available, more applications of 3D city models could be potentially explored in different aspects of life in small island states, such as natural disaster management and forecasting, urban navigation and virtual tours, civil infrastructure management, solar envelope determination, and energy demand assessment (Biljecki et al., 2015a). Since Grenada already invested in expensive LiDAR data, it is recommended for the government to share LiDAR data with the public. Sharing LiDAR data can support and spur operational applications and scientific studies, which can improve the citizen engagement and create more economic and societal benefits.

4.4 Conclusions

This research developed a novel methodology for Grenada to estimate and map in-use road and building material stocks and improved previous material stock account. In recent years, studies of material stock have entered the hot research period and become popular in the world’s large economies, such as Japan, the United States, China, and the EU25. Rapid urbanization and industrialization, as well as adverse climate impacts, have exerted pressure on small island states to resolve the contradiction between high demand and limited material resources. To better understand and manage resources, quantification and mapping of in-use material stocks are necessary. Material stock research on small island states is in the exploration stage and faces distinct difficulties because of the data quality and availability problems. This study intended to improve current material stock accounting approaches for small island states from two perspectives: road stocks and building stocks, and Grenada was chosen as the study area. In terms of road stocks, a novel GIS-based bottom-up approach was developed to estimate, map, and analyze in-use road stocks and the first road material stock account for Grenada as well as the Caribbean region was generated. This study showcases the important role of road stocks in socio-economic metabolism and lays the groundwork for future research into road stock accounting and analysis. In terms of building stocks, this study improved the previous building stock accounting approach for Grenada by combining GIS footprint data with LiDAR elevation data to obtain accurate building height information. To further understand how the approach used in this study can improve previous building stock accounting for Grenada and also other small island states, a comparative review was conducted to compare this study with previous two material stock studies in Grenada. This research also explored the application of material stocks and generated 3D building models and the first 3D WebGIS application for Grenada integrating material stocks with 3D city models. These products provide policy makers and practitioners new insights into material stocks and 3D city models and allow the public to easily access and navigate the complex material stock geodatabase.

Grenada shares many similarities with other small island states, which indicates that the methodological approach and the recommendations of this study are potentially applicable to other small island states. More research could be conducted exploring and monitoring the material stock status in different small island states and improving current accounting methodology by integrating high-quality data from multiple sources. Moreover, future research on small island states could investigate the life cycle of materials and explore the recycling potential of in-use material stocks, which allow policy makers and planners to better manage material inflows and outflows and plan for sustainable development.

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Appendix A

Table A.1. *Metadata for the Grenada geodatabase.*

Description	Type	Date	Attributes	Source/credits
Road network	Shapefile	Jan. 1, 2014 - Dec. 31, 2015	Polyline, general road type	Caribbean Handbook on Risk Information Management (CHARIM) http://charim-geonode.net/people/profile/grenada/?content=layers
Building footprints	Shapefile	Jan. 1, 2014 - Jan. 1, 2015	Polygon, use type, occupancy class, floor area, gross floor area, building code, material intensity, number of stories, material stock information, service type	
Parish boundaries	Shapefile	Current	Polygon, boundaries	
Country boundaries	Shapefile	Current	Polygon, boundaries	
Census enumeration districts	Shapefile	Current	Polygon, boundaries	
Digital Elevation Model (DEM)	Raster	2016	Elevation data	
River	Shapefile	2016	Polyline, node, length	
Transportation ports	Shapefile	2016	Polygon, airport or seaport	
Hurricane shelters	Shapefile	2016	Polygon, location, name, type	
Quarries and waste disposal sites	Shapefile	2016	Polygon, quarry type, area	
Demographic data	Shapefile	Jan. 1, 2014 - Jan. 1, 2015	Polygon, enumeration district ID, population statistics	
Population per building	Shapefile	Jan. 1, 2014 - Jan. 1, 2015	Polygon, enumeration district ID, parish name, occupancy, use type, population	
Land use	Raster	Jan. 1, 2014 - Jan. 10, 2015	Land use classification	
Landslide inventory	Shapefile	Jan. 1, 2005 -	Polygon, occur in year 2015 or not, slide type, failure	

		June 1, 2015	type, material type, post Ivan or not	
Landslide susceptibility	Raster	2016	Susceptibility level	
Soil inventory	Shapefile	Jan. 1, 2014 - Jan. 1, 2015	Description, gridcode	
Households by parish	Data table	1981, 1991, 2001, 2011	Number of households	Grenada National Census
Dwelling type	Data table	2001, 2011	Dwelling type, number of households	
Households by counstruction material	Data table	2001, 2011	Construction material, number of households	
Household by roofing material	Data table	2001	Roof material, number of households	
Household by wall material	Data table	2001, 2011	Wall material, number of households	
Damages to Gov't, Health, Education and Transportation Sectors from Hurricane Ivan	Data table	2004	Facility type, sector, location, parish, damage assessment	Grenada, Hurricane Ivan - Preliminary Assessment of Damages, September 17, 2004 - The World Bank
Housing Damages, Hurricane Ivan	Data table	2004	Percentage of housing by parish with different levels of damages	
Damage by tourist accommodation n, Hurricane Ivan	Data table	2004	Sample of room damage by tourist accommodations.	
Tourist accommodation ns functionally closed, Hurricane Ivan	Data table	2004	Accommodation name, town, parish, % of country's room capacity, % of country's bed capacity	
Estimated affected population, Hurricane Ivan	Data table	2005	Affected population by parish	
Building footprints	Shapefile	2018	Polygon, name, type, craft, amenity, admin_level, barrier, boundary, shop, office, man_made, tourism, other tags	Open Street Map: Volunteered Geographic Information © OpenStreetMap contributors https://www.openstreetmap.org/#map=12/12.1058/-61.6875

Road network	Shapefile	2018	Polyline, name, road hierarchy, surface material, barrier, order	
Building application information	Data table	Jan. 2008 - Sept. 2017	Proposed use, parish, floor area	
Land cover map	Shapefile	2009	Land use	Grenada Physical Planning Unit and Ministry of Agriculture, Forestry and Fisheries, Government of Grenada
Digital Terrain Model (DTM)	Raster	2017	Elevation data for town of St. George's (LiDAR-derived product)	Permission from Land Use Division, Ministry of Agriculture, Forestry and Fisheries, Government of Grenada
Fieldwork photo	Photo	2017	Photo file path, File name, DateTime	Rob Symmes, 2017

** Coordinate system: WGS 84; Datum: World Geodetic System 1984; Details can be found in metadata stored in each geodatabase feature class*

Appendix B

Table B.1. *Material intensity typologies in different building occupancy classes in Grenada (Symmes et al., 2019, cited in De Kroon, 2020, pp. 104-105). Unit:* kg/m^2

	Aggregate	Timber	Concrete	Steel	Relevant occupancy classes
Concrete Structure type 1					Urban-area single-family dwelling; Rural-area single-family dwelling; Residential-area single-family dwelling
Foundation - Pad footings	45	0	45	1	
Foundation - Posts	0	0	300	5	
Floors	0	0	450	10	
Walls	0	0	520	1	
Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	10	
Total	**45**	**40**	**1315**	**27**	
Concrete Structure type 2					Church/Chapel; Educational campus building; Standalone elementary/ secondary school; Minor hospital/Health center; Government office; Commercial; Urban-area mixed commercial; Industrial; Urban-area commercial/dwelling mix; Urban-area single-family dwelling; High density-area apartment; Low density-area apartment; Rural-area single-family dwelling; Residential area single-family dwelling; Small hotel cottage/villa; Recreational/community center; Seaport; Bus terminal
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**	**1645**	**36**	
Timber Structure					Urban-area single-family dwelling; Rural-area single-family dwelling; Residential area single-family dwelling
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					Urban-area single-family dwelling; Rural-area single-family dwelling; Residential area single-family dwelling
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**	**1125**	**35**	
Steel Structure					Industrial
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**	**1645**	**325**	
Brick Historical Structure					Cathedral; Historic building
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	0	20	
Walls	0	50	0	0	
Roof - Frame	0	40	0	0	
Roof - Covering	0	0	0	0	
Total	**159**	**90**	**675**	**35**	
Reinforced Concrete Structure					Major hospital; Large multi-unit hotel building; Stadium; Airport
Foundation - Strip footings	135	0	225	5	
Foundation - Ground slab	24	0	450	10	
Floors	0	0	450	10	
Walls	0	0	0	145	
Roof	0	0	0	10	
Total	**159**	**0**	**1125**	**180**	

Table B.2. *Final material intensity typologies in different building occupancy classes in Grenada. Unit: kg/*m^3.

	Aggregate	Timber	Concrete	Steel
Concrete Structure type 1	14.76	13.12	431.43	8.86
Concrete Structure type 2	52.17	13.12	539.70	11.81
Timber Structure	14.76	29.53	113.19	11.81
Concrete/Timber Mix Structure	52.17	29.53	369.09	11.48
Steel Structure	52.17	0	539.70	106.63
Brick Historical Structure	52.17	29.53	221.46	11.48
Reinforced Concrete Structure	52.17	0	369.09	59.06