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Infrastructure, Risk, and Resilience on Small Island Developing States (SIDS): Navigating the Nexus

Part 1: Conceptual Foundations

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ABSTRACT

Two-thirds of the Sustainable Development Goals (SDGs) depend on infrastructure investment, as they are the backbone of production, consumption and our daily life, hence the material basis of societal well-being. As economies develop, the demand for new and/or improved services rise, such as transport, sanitation, education, and health. These services are delivered by infrastructure (also referred to as 'material stocks' or simply 'stocks') that drive a self-reinforcing cycle of resource consumption: to first build and then to maintain and operate the stocks, creating a "lock-in-effect". From a sustainability perspective, it is necessary to observe the relationships between infrastructure development, resource demands, and the societal services stocks provide, referred to as the "stock-flow-service" (SFS) nexus.

Small Island Developing States (SIDS) suffer disproportionally from the adverse effects of global warming such as hurricanes, flooding, droughts, and sea level rise. Between 1970 and 2020, SIDS collectively lost $153 billion from extreme events, largely from infrastructure damage and the consequent breakdown of critical services. Constrained by their small size and available resources, SIDS rely heavily on imports for most of their construction needs, often through complex supply-chain configurations increasingly threatened by volatile markets, rising transport costs and geopolitical concerns.

At the same time, service needs from infrastructure are also changing in SIDS. Climate impacts are escalating the need for hard-engineering climate adaptation measures such as sea-walls, groynes, dykes, or artificial islands, hence driving the demand for more resources. Unplanned and unrestrained infrastructure development heightens the risk of maladaptation, especially in climate-vulnerable SIDS. By recognizing the complex dynamics of material stock, flows, and service provision, policymakers can mitigate systemic risks and safeguard the long-term well-being of island societies.

Keywords: Small Island Developing States (SIDS); island sustainability; socio-metabolic risk (SMR); material stock-flow-service nexus.

KEY MESSAGES:

- Infrastructure is the backbone of society, driving economic growth and delivering essential services.
- Increasing demands for infrastructure and associated services lead to a reinforcing cycle of resource consumption, known as the 'stock-flow-service' (SFS) nexus.
- Small Island Developing States (SIDS) face unique challenges to their infrastructure due to their susceptibility to climate change impacts.
- SIDS are on a path of resource-intensive and costly climate adaptation measures that exacerbate vulnerability in multiple ways.
- Understanding the relationship between material stock-flow dynamics and societal needs is crucial for mitigating 'socio-metabolic risks' and fostering sustainable development in SIDS.

Photo: Rock revetments protects coastal erosion and salt water infiltration in Mauritius.

INTRODUCTION

THE IMPORTANCE OF INFRASTRUCTURE IN THE CONTEXT OF SMALL ISLAND DEVELOPING STATES

Infrastructure serves as the backbone of society. It drives economic development and growth, and delivers essential services, including healthcare, education, and justice across various sectors such as energy, water, waste management, transport, communications, and social services. **In the context of this brief, infrastructure refers to the engineered built environments such as buildings, roads, sewage systems, hospitals, and other production facilities.** Infrastructure plays a pivotal role in achieving the UN Sustainable Development Goals (SDGs), directly and indirectly contributing to 121 out of 169 targets (Thacker et al., 2019). For example, it directly determines SDG 9 (industry, innovation, and infrastructure) while also influencing targets under SDG 1 (no poverty) by providing access to social infrastructure and economic opportunities, and SDG 17 (partnerships for the goals) by facilitating digital and communication infrastructure for data sharing and collaboration (van Zanten & van Tulder, 2021). It's cross-cutting roles underscore the importance of infrastructure in advancing many global development goals. Conversely, bad or redundant infrastructure is detrimental to sustainability and wellbeing, reflecting higher per-capita energy use, carbon emissions (Haberl et al., 2023) and increasing the demand for material resources (Duro et al., 2024).

Infrastructure investment is a large part of the trillion-dollar global capital industry; it is projected to require a total of US$94 trillion in capital investment by 2040 (Thacker et al., 2019). However, extreme events exacerbated by climate change are outside the tolerance limit of some existing infrastructure, rendering them obsolete and causing service disruption. The global Average Annual Loss (AAL) related to infrastructure is between $732-$845 billion (CDRI, 2023). Unsustainable and unplanned infrastructure development thus creates significant negative impacts on global economies.

Small Island Developing States (SIDS) are particularly vulnerable to climate change impacts (UNDP, 2024; Keo & Jo, 2023; Climate Watch, 2024). This is mainly because their centres of population, economic activity and transport infrastructure tend to be co-located on coastal plains. Their narrow economies, small size, limited resources, and locations in disaster-prone regions amplify the impact of these challenges, making SIDS early warning systems for broader global trends (Stöfen-O'Brien et al., 2022).

The susceptibility of SIDS to disasters is illustrated by their position on the Notre-Dame Global Adaptation Index (ND-GAIN). The ND-GAIN highlights that 10 out of the 19 countries most exposed to climate change are SIDS (Brownbridge & Canagarajah, 2024). Climate change-driven damages to physical and social infrastructure imposes substantial costs, exemplified by the devastating losses experienced during events like Hurricane Maria in 2017 that cost Dominica an estimated US $1.46 billion, or approximately 260% of its GDP (Wallemacq & House, 2018) or Hurricane Irma that same year that cost Antigua and Barbuda more than $136 million of which tourism industry damages accounted for 44% (Mowla, 2024).

In the *Antigua and Barbuda Agenda for Small Island Developing States: A Renewed Declaration for Resilient Prosperity (ABAS)*, SIDS have recognised that "adapting sustainable infrastructure" is necessary for fostering safe, healthy and prosperous societies (United Nations 2024). Understanding and supporting SIDS' economies necessitates a comprehensive examination of their infrastructure and its role in resilience-building efforts. Failure to address these issues could lead to further significant economic losses, with SIDS already having lost US$153 billion from extreme events between 1970 and 2020 (GCA, 2024) mostly from infrastructure damages and loss of associated services. Reconstruction needs have contributed to some 40% of SIDS reaching unsustainable levels of debt, with 70% of SIDS' public debt ratios exceeding 40% of GDP, hindering their ability to invest in resilience and climate action (Bharadwaj, 2024). Furthermore, the 2023 Adaptation Gap Report estimates the per capita adaptation finance needs of SIDS to be US$153 on average - the highest among all low, medium, and high-income countries globally (United Nations Environment Programme, 2023).

However, access to financing is difficult since SIDS do not qualify for concessional loans, as the World Bank classifies most SIDS as middle- and high-income countries (Fresnillo & Crotti, 2022). This measure does not take into account the relative fragility of SIDS economies, when a single severe event can result in a major recession (Bishop et al., 2023). Furthermore, policies like catastrophe bonds, designed to pay issuers when disasters strike, can disqualify SIDS from insurance financing. For example, after Hurricane Beryl, Jamaica did not receive a payout because the bond terms required an air pressure threshold that was not met (Ritchie et al., 2024). After lengthy debates, the United Nations adopted the Multidimensional vulnerability Index (MVI) for SIDS that recognized the unique complex of development challenges they face (United Nations, 2024).

Photo: Tetrapod seawalls in Malé city in the Maldives, built primarily with Japanese financial assistance and construction materials.

BACKGROUND

UNDERSTANDING THE "STOCK-FLOW-SERVICE" NEXUS

Resource use in social systems mirrors biological processes. Just as organisms consume resources for sustenance and reproduction, societies deliberately mobilize materials and energy to sustain and grow their populations. Some of these materials leave the system in a short time in the form of waste, such as excrements, discarded food, paper, packaging materials, and other organics. However, a significant proportion stays in the socio-economic system and accumulates as net additions to 'material stocks (or 'stocks'). This proportion includes built infrastructure and all durable products such as machines, automobiles, household appliances, and electronics.

Stocks provide societal services such as housing, transport, communication, sanitation, food and energy provisioning (Whiting et al., 2020), which in most cases requires additional flows (e.g., energy used to propel cars or drive machines). These stocks have useful lifespans of years to many decades, yet eventually lose their usefulness and become wastes.

Infrastructure development and its associated services are resource-intensive. Globally, approximately 75% of all materials extracted worldwide are used to build up new material stocks or to maintain and operate them (Krausmann et al., 2020). Material flow accounting demonstrates that over 50% of extracted resources now go into building stocks, up from 20% in 1900. In addition, "stock" patterns and dynamics influence current and future "flows" of resources (first for building up and then for maintenance and operation) creating lock-in effects and path-dependencies (Krausmann et al., 2017; Seto et al., 2016).

As economies grow, the need for new or enhanced services rises, creating demand for more infrastructure. This creates a self-perpetuating cycle of resource consumption for construction and their ongoing maintenance and operation. The larger the stocks, the more socio-metabolic flows are needed to maintain and operate them, supporting a reinforcing loop called the material "stock-flow-service" (SFS) nexus (Haberl et al., 2021).

Figure 1. Dynamic feedback between stock, flows and services, creating a lock-in effect

THE STOCK-FLOW-SERVICE NEXUS IN THE CONTEXT OF SIDS

To take an example, the rapid growth of tourism in SIDS drives economic growth, which drives substantial investment in infrastructure like airports, ports, and hotels, leading to increased demand and imports of construction materials. Several SIDS (e.g., Mauritius and Seychelles) also depend on construction workers and service staff from low-income countries to meet their growing need for infrastructure and tourism industry development. In turn, more homes are needed to house these workers, and to absorb their waste, necessitating the expansion of existing landfills. The case study on the limits of tourism growth in Aruba clearly illustrates the interconnected relationship between stock-flow dynamics related to the growth of the tourism sector (Jurgens et al., 2024).

In SIDS, the building and upkeep of infrastructure is more expensive than for countries on the mainland, and can suffer losses twice. First, the initial investment is higher due to heavy reliance on imports of construction materials. And second, when struck by disasters causing infrastructure damage, it brings on the cost of reconstruction (Bishop et al., 2023). In SIDS, studying this nexus is crucial for understanding where the need for infrastructure originates, how this demand is met, and what the trade-offs are from a sustainability perspective.

Furthermore, adaptation to climate change is driving the growth of new types of infrastructure such as sea-walls, groynes, dykes, or artificial islands (Baills et al., 2020; Duvat, 2020) (Figure 2). Procuring resources required for such projects is becoming a challenge due to rising geopolitical concerns (Hossain, 2024). Factors such as increasing transportation costs, reliance on outside technologies, often those proposed by donors, high-interest loans, and rapid environmental changes can create resource scarcity and dependencies. Resource scarcity remains a hurdle to many SIDS for achieving sustainable development and infrastructure (Bishop et al., 2023). The reality of volatile materials prices in the global commodity market in tandem with scarcity due to heightened global demand from population growth, has also resulted in a degree of de-globalisation as countries want to hold on to their resources instead of exporting them.

Figure 2. Resource-intensive adaptation measures - sea-walls against coastal erosion and salt water infiltration in Mauritius (left) and Maldives (right). Photos by Simron Singh.

CONSIDERATIONS

SOCIO-METABOLIC RISKS, TIPPING POINTS, AND COLLAPSE

Unrestrained material growth, or unsustainable patterns of resource use will eventually jeopardize system resilience. Specific configurations and combinations of material stocks and flows in a system accumulate "socio-metabolic risk" (SMR) over time (Singh et al., 2022). **SMR is to islands as circulatory health problems are to humans – both constrain the entity's ability to withstand significant shocks and changes.** Examples of maladaptive resource-use configurations to climate change include the concentration of infrastructure along the coast, high import reliance, tourism industry dependency, overexploitation of local resources, undiversified exports, centralized energy systems and hard-engineered solutions to adapt to climate change.

Often when problems arise or when faced by a shock, responses tend to be short-term, symptomatic quick fixes, leading the system into a "socio-metabolic trap". The 'reclamation-fortification island model' in the Maldives is an iconic example of a socio-metabolic trap. Unrestrained dredging from the seabed causes damage to the reefs and coastal areas that prohibit the natural growth required to adapt to rising sea levels. Moreover, such projects rely on import of huge volumes of construction materials with external financial and technological solutions that raise concerns about whether the Maldives can afford and maintain the necessary structures to contain climate risks, especially as more disasters may reduce tourism revenue, and international funding is uncertain (Duvat, 2020).

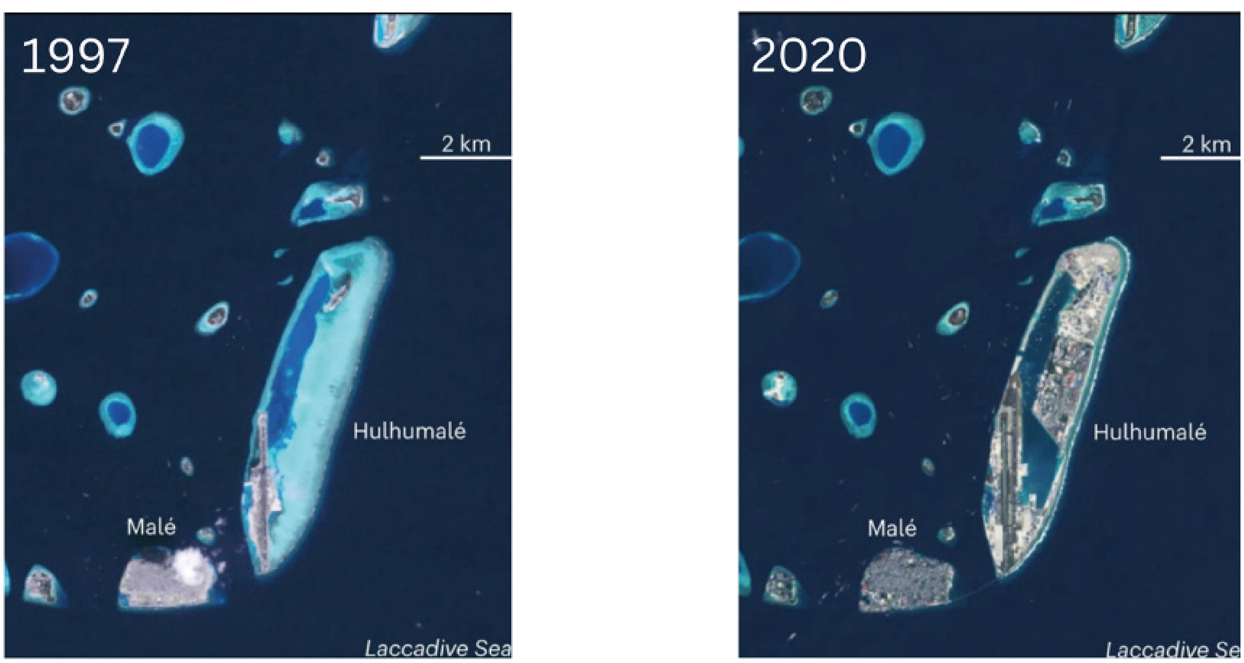

Figure 3. Land Reclamation of Maldives between 1997 & 2020 (Source: Chase-Lubitz, 2024; Lauren Dauphin/NASA Earth Observatory, 2021[1])

An example of the socio-metabolic trap in Mauritius is the growing reliance on active cooling systems to address poor indoor conditions and adapt to climate change, which increases emissions. A more nature-centric solution would involve considering fundamental green

[1] NASA Earth Observatory images by Lauren Dauphin, using Landsat data from the U.S. Geological Survey.

building paradigms. Similarly, to resolve the problem of flooding due to climate change, in part caused by increased impermeability resulting from conversion of green fields into residential and commercial developments, drain networks are considered. This ends up reducing the fresh water reserves that can be retained on the island, and lead to a chain of adverse environmental impacts such as erosion of fertile land into the sea, and importantly the prevalence of flooding and droughts simultaneously over a given year.

With 'resistance to change' (Huang, 2010), SMR spreads, reinforces itself, and cascades into further risks across the system in a non-linear domino effect (Klose et al., 2021). Increasing SMR at some point may also push island systems toward a tipping point, a change beyond which the system permanently reorganizes itself. An adverse outcome of this process is a socio-metabolic collapse (SMC) (Singh et al., 2022) (Figure 4).

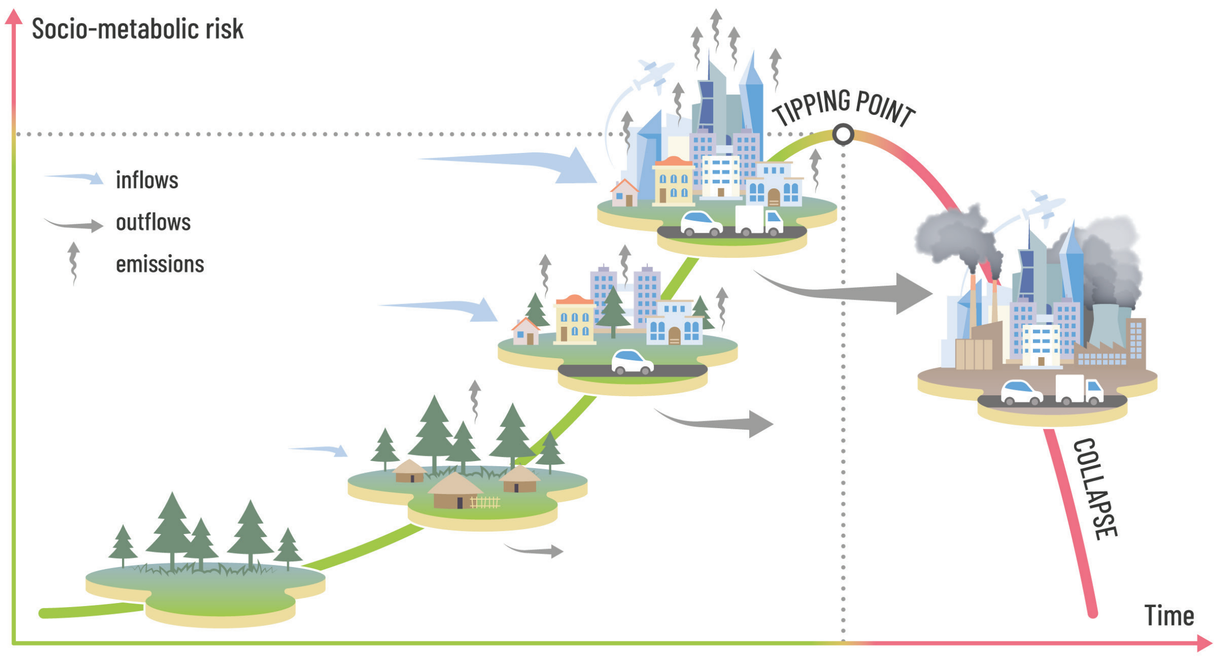

Figure 4. Accumulating socio-metabolic risk through unrestrained infrastructure development

Case studies from Antigua and Barbuda (Bradshaw et al., 2020), the Bahamas (Martin del Campo et al., 2023) and Grenada (Symmes et al., 2019) highlight how maladaptive infrastructure development exacerbates SMR in island systems. All three countries are SIDS that rely on their respective tourism industries as a major economic driver which leads to practices such as concentrated urban development in coastal areas and underdeveloped areas and limited infrastructure in other parts of the country amongst others. In Antigua and Barbuda for instance, the YIDA International development project involved the sale of over 2000 acres of coastal land within a marine protected area to establish an 'economic zone'- leading to the loss of 75% of natural infrastructure such as mangrove trees and associated biodiversity. This cascaded into a loss of local livelihoods, limited opportunities for economic diversification, and increased exposure to the effects of hurricanes and flooding, creating a negative feedback loop for the economy (Bradshaw et al., 2020).

Figure 5. Time lapse of the Bahamas showing urban development leading to coastal squeeze: 1990 versus 2025 (source: Google Earth)

Similarly, in the Bahamas (Figure 5), dense urban development has damaged ecologically sensitive areas which may impact hydrological cycles in the future, further impacting people and biodiversity. The concentration of development in coastal regions results in coastal squeeze - a thinning of the coastal zone and its natural infrastructure - and displaces populations to underdeveloped inland zones. Unregulated development in coastal areas or other hazard-prone zones puts people and infrastructure at risk (Martin del Campo et al., 2023). Grenada faces parallel challenges where the destruction of buildings and infrastructure from natural hazards necessitates large-scale reconstruction, further stressing the environment and economy due to the reliance on costly material imports (Symmes et al., 2019). These examples illustrate the cascading risks and potential for socio-metabolic collapse when islands pursue development paths that are misaligned with their environmental and socio-economic realities.

Importantly, the stock-flow nexus is often based on a system's sustained or growing state. While some flexibility can help manage certain shocks, more severe shocks can overwhelm these systems. As climate change advances and technology evolves rapidly, it's crucial that SIDS plan for more extreme shocks that could threaten their very existence. Building resilience must be future-proof, preparing these islands for both present and future challenges.

Photo: Massive construction of high-rise apartments on Hulhumalé, a reclaimed island north of Malé, the capital island city in the Maldives. Nearly all construction materials and labour come from India and China.

CONCLUSION

Addressing the complex challenges SIDS face requires a comprehensive approach that integrates sustainable infrastructure development with environmental stewardship, social equity, and economic resilience. **By recognizing the interconnectedness of material stock, flow, and service provision within the SMR framework, targeted strategies to optimize land-use planning, diversify economies, reduce external resource dependency, and closing material loops are urgently needed.** For this, partnerships for data sharing on stocked materials, their life spans, and the capacity to harness these materials are essential for informed decision-making in climate adaptation and resilience planning. It is imperative for SIDS to shift from symptomatic solutions to systemic interventions that address the root causes of vulnerability and mitigate SMR.

The second part of this brief will detail key policy recommendations to enable SIDS to promote long-term sustainability, and become leaders in climate action.

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