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ORIGINAL ARTICLE

Realities of bridge resilience in Small Island Developing States

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Abstract
Small Island Developing States (SIDS) are acknowledged as particularly vulnerable to extreme climate events; however, the realities for transport infrastructure and bridges are still poorly studied. Assessing bridges in this context can be challenging due to data scarcity, a lack of local standards, and uncertainty due to climate change. While bridges are designed to connect transport networks, they also carry energy, water, and communication networks, making them critical cascading failure points worthy of special attention in terms of risk assessment and resilience measures. We explore what resilience actually means for the design and management of SIDS bridge infrastructure by applying a post disaster forensics and systems approach that is not reliant on complex methods or large amounts of data. To demonstrate the practicality of our approach, we apply it to the island of Dominica, which is regularly impacted by both tropical storms and hurricanes. Our results document the extreme conditions for infrastructure and nearby settlements and the complex interrelated physical processes that occur during these events. We reflect on the implications for design approaches for bridges under these conditions and detail specific recommendations on how the resilience of existing and new bridges can be enhanced through practical measures that are achievable, even within the constraints experienced by those managing bridge infrastructure in SIDS contexts. This work adds to the growing number of studies exploring forensic disaster investigation and systems thinking, but is the first to explore bridge resilience in SIDS.

Keywords River bridges · Resilience assessment · Road infrastructure · Small Island Developing States · Dominica

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1 Introduction

Natural hazards related to intense weather events such as cyclones and hurricanes can cause widespread damage to infrastructure and potential loss of life where they make landfall. These extreme events are becoming more frequent and more extreme due to global warming (Emanuel 1987; Collins and Walsh 2017; Pörtner et al. 2022) and there is an urgent need for society to prepare for the impacts of these changes (Dilling et al. 2015). This change in climatic conditions will also bring more extreme river flows and ocean storm surges (Zhang et al. 2020), which will expose infrastructure in proximity to rivers, to conditions beyond those originally envisaged by their designers and the design codes previously and currently used. This tends to result in an increase in infrastructure systems failures, in particular through the failure of critical connections within these systems, such as bridges, which are at the direct interface with these more extreme river flows.

Of course, not all countries will be affected to the same extent by these changes, and some will be more vulnerable than others. In addition, not all countries could be considered resilient to current climate, let alone future climate (Kelman 2018). In this paper, we focus on climate resilience in Small Island Developing States (SIDS), which are particularly vulnerable to extreme climate events. SIDS vulnerability and their high exposure to natural hazards have long been recognised and studied (Encontre 1999, Scandurra et al. 2018, World Bank 2022). They are by their physical nature surrounded by ocean, isolated and small, and are also located in climate zones that put them in the path of extreme climatic events such as tropical storms, cyclones, and hurricanes (Bundhoo et al., 2018). SIDS are located in four main geographical regions: the Caribbean, the Pacific, coastal West Africa, and the Indian Ocean (UNCTAD 2014). There are many recent studies that highlight SIDS specific vulnerabilities to current and future climate, for example, in coastal infrastructure (Banerjee et al. 2018), energy infrastructure (Bundhoo et al. 2018), information management (Mackay et al. 2019), and international transport (Monioudi et al. 2018), to name but a few. However, there are currently very few studies that look at bridge infrastructure resilience in SIDS, despite the scale of reported damages to these structures during extreme events (Padgett et al. 2008).

Bridges are a particularly important example of critical infrastructure. Although bridges are primarily designed to connect transport networks, they are also used to carry connections for energy, water, and communication networks, making them failure points in multiple infrastructure networks and therefore worthy of special attention in terms of risk assessment and resilience measures (Pregnolato 2019; Linkov et al. 2014). Hydraulic action is considered to be the number one cause of bridge failure, causing 53% of failures in a study of 503 bridges in the USA (Wardhana and Hadipriono 2003). Hydraulic actions relate to the interaction of a dynamic river system with the bridge structure and include hydrostatic and hydrodynamic forces, floating debris impacts, sediment deposition, and scour. These water risks will be exacerbated in the future, with increased river flows and debris transport, not only brought on by a changing climate, but also as a result of more direct human activities on the river system such as deforestation of catchments, obstruction of floodplains, and other modifications to the river systems (Nasr et al. 2019).

There is a lack of basic research in the SIDS context, particularly when it comes to river infrastructure, despite the acknowledged high levels of exposure to natural hazards (Nurse et al. 2014). A systematic literature review by Méheux et al. (2007) attributes this lack as partly due to wider research biases between developed and developing countries and highlights that what documentation is available are mainly post-disaster assessment reports, which by necessity only focus on the impact, and the specific causes or implications are not discussed.

There are also no locally specific bridge design standards for most SIDS countries, and this can result in the application of multiple differing international standards, from different funders and consultants, perhaps more appropriate for other climates and contexts. This can result in sub-optimal performance under local SIDS conditions and complications for long-term maintenance by authorities. SIDS in general have a significant challenge in this regard, and even where standards are officially adopted, it is usually necessary to draw on more than one international standard to ensure some relevance in different areas of bridge design to the local context. For example, Fiji uses a combination of UK, Australian, and New Zealand standards in their bridge design (Amir-Ansari 2013) for historical, concrete supply, and geographical reasons, respectively.

A broad definition of resilience is the ability to respond to and recover from a disruptive event (Hosseini et al. 2016). While it could be argued that engineering to some extent has always been concerned with resilience in a general sense, it is only relatively recently that resilience as it applies to infrastructure, from a systems perspective, has become a specific research focus (Banerjee et al. 2019; Gay and Sinha 2013). This adoption in engineering was driven to some extent by the huge impacts of Hurricanes Katrina, Irene, and Sandy on infrastructure in the USA (Minaie and Moon, 2017). The broad use and study of resilience illustrates that it is not just a technical engineering challenge, but is related to the wider systems that technical engineering practice operates within, i.e. economic, social, and organisational (Hosseini et al. 2016). Resilience has been adopted as a framework for disaster management within the international community, driven strongly by The Sendai Framework for Disaster Risk Reduction 2015–2030 and the United Nations' Sustainable Development Goals calls for action to "build back better" in ways that leave no one behind. These drivers are certainly evident in the Caribbean post Hurricane recovery context (Popke and Harrison 2018).

So, if we are to explore resilience as it applies to bridge structures, as well as understanding the technical aspects of the structure, we need to be cognisant of its environmental context, socio-economic context of its design, construction, and long-term maintenance. But how do we implement and measure resilience in practice, and how do we apply this to the SIDS context? There have been attempts at providing frameworks for measuring and studying resilience in bridges (e.g. Minaie and Moon 2017; Ikpong and Bagchi 2015); however, these tend to rely on good quality data, highly technical methods, and are often tested on only a handful of bridges. These limitations make these frameworks hard to apply in poor data contexts (Minaie and Moon 2017), such as SIDS, and there is very little evidence of these methods being used in practice outside academia. Indeed, even applying these bridge resilience methods on a wider scale in developed countries, where data and technical capacity is more readily available, is hampered significantly by data sharing issues and lack of information (Pregnolato 2019).

Given the challenges in studying bridge resilience in the SIDS context outlined above, we chose an approach that is holistic by carrying out a post event forensic style analysis to document what happened to bridges and compare this to the standard methods commonly used on the islands to design bridges. We use a synthesis of methods as part of our resilience investigations: novel data collection methods, numerical modelling (hydrology and hydraulic), engineering calculations, remote sensing, and post-event drone images and videos. This approach is partly inspired by the growing body of work in post disaster systems analysis (Burton 2010; Keating et al. 2016), but also evolved as a practical response to the sometimes overwhelming scale of challenges faced by SIDS.

We use the Caribbean Island State of Dominica as our SIDS study focus, due to significant damages experienced there following tropical storm Erika in 2015 and hurricane Maria in 2017 (Commonwealth of Dominica 2017). These events also caused high levels of damage across many other Caribbean SIDS. The Caribbean continues to experience these large-scale multiple island impacting events, and in 2020 alone, the Atlantic hurricane season produced 30 named storms, 14 hurricanes, and 7 major hurricanes (Klotzbach et al. 2022).

The objective of this paper is therefore to provide analytical and managerial insights on how to deal with bridge structures in SIDS and other similar extreme contexts, particularly where resources and capacity are limited. We use low-cost and simple open-source approaches, both for data collection and analysis, to carry out vulnerability assessments of bridges under extreme conditions, cognisant of the realities of local capacities and the use of standard methods applied by international consultants. From this assessment, we identify practical actions to increase bridge resiliency in extreme conditions, generally and for SIDS in particular.

2 Dominica SIDS context

Many SIDS have relatively simple road systems, and destroyed bridges often result in a complete breakdown in the transport network, hampering relief and recovery (World Bank 2022). While damage is largely due to the extreme magnitude of climate events, it is exacerbated by the general development challenges within Small Island States due to their geographical and socio-economic constraints (Barclay et al. 2019). Bridges and roads are commonly sited at the base of steep terrain following the coastline and are exposed to flooding and landslides, and Dominica is a good example in this regard (Fig. 1b). With limited budgets and technical capacity to reconstruct and maintain infrastructure, even under more benign conditions, these disasters set back development significantly due to these reoccurring disasters. Improving the resilience of existing bridges and new build structures to these extreme events is therefore of the utmost importance in accelerating infrastructure rebuild and economic recovery.

Dominica is an island nation located in the chain of islands in the Eastern Caribbean (Fig. 1a), at 15.46 N and 61.35 W. It is approximately 751 km^2 in area, and 47.8 km long (N-S) by 25.9 km wide (W-E). It is a steep volcanic island covered in tropical rain forest and is known as the "The Nature Island of the Caribbean". Land rises steeply into the interior from the coast to a maximum elevation of 1447 m and mean topographical slope of 24.4 degrees, and the furthest point from the coast is 10.1 km. The country has a population of 71,808 as of 2019 (DESA 2019). Most of the island's infrastructure is located along the coast, where most of flatter terrain can be found. Our own analysis of building proximity to the coast reveals that 90% of the island's infrastructure is located within 3.25 km of the coast and 70% is within 1 km.

Dominica lies in the area influenced by the intertropical convergence zone, with changes in wind patterns and increased rainfall during the July to October hurricane season (Barclay et al. 2019). Together with the steep topography, the high intensity rainfall, and the winds associated with these climate events, Dominica experiences extreme climatic conditions across the whole island during these events, as is typically the case with most SIDS. Two particular recent climate events, Tropical Storm Erika in 2015 and Hurricane Marie in 2017, caused widespread damage across the Caribbean, including Dominica. Hurricane Maria caused significant loss

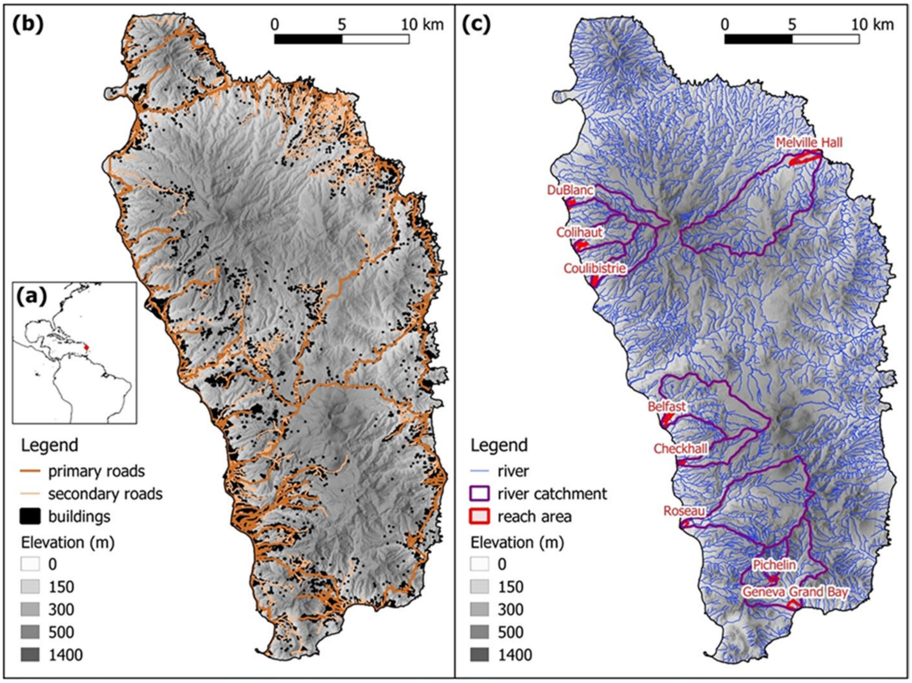

Fig. 1 (a) Location of Dominica in the Caribbean, (b) Road and building proximity to the coast, (c) Bridge river reaches studied and their catchments

of life and damage to 70–90% of infrastructure across multiple islands, including the loss of many bridges. A Post-Disaster Needs Assessment for Dominica estimated that Hurricane Maria resulted in total damages of US$931 million and losses of US$380 million, and for comparison, this amounts to 226% of the 2016 gross domestic product (Commonwealth of Dominica 2017). Following the events of 2017, the President of the Commonwealth of Dominica, Prime Minister Skerrit addressed the United Nation's General Assembly, declaring an international humanitarian crisis and pledging to make Dominica the world's first climate-resilient nation (Popke and Harrison 2018).

The nine priority river reaches were identified by the Ministry of Public Works, Water Resource Management, and Ports (PWWRM&P), Government of Dominica, and are the focus of this paper: Melville Hall, Roseau, Geneva Grand Bay, Belfast, Coulibistrie, Dublanc, Colihaut, Checkhall, and Pichelin (Fig. 1c). Two of the reaches (Checkhall and Melville Hall) are located immediately adjacent to the two airports on the island. Five of the reaches are located on the West side of the island and two reaches are located in the South. Roseau, the islands capital is located centrally on the West coast and Melville Hall on the East of the island. All the reaches are close to the coast, with the exception of Pichelin, which is situated at the confluence of two major tributaries ~ 3 km inland. There are a total of 19 bridges on the high priority river reaches, with 16 classed as important.

3 Data and methodology

One of the challenges of applying technical assessments in the SIDS context is the general lack of data resulting from low technical capacity and limited investment in long-term measurement infrastructure, for example, in hydromet services (Cashman 2014). The extreme climate also hampers efforts to collect event data, as equipment is often damaged during extreme events. Our choice of methodologies is therefore constrained by data availability as well as the practicalities of the SIDS context. We applied three basic principles for our assessment in the choice of data and methods: (i) use available local data where possible, and supplement this with novel low-cost rapid collection methods that could be used locally; (ii) apply modelling and engineering standards that are applied when designing and modelling bridges in these contexts; and (iii) take advantage of recent innovations in open data such as satellite remote sensing, and in particular image and video sharing on social media by local residents.

We synthesise this mixture of data and methods, in a systems and post-disaster forensics approach (Keating et al. 2016; Burton 2010), to assess and document what processes are relevant to bridge structures and their environmental context, in order to learn as much as possible about the resilience of bridge structures, as well as documenting failure mechanisms of damaged or destroyed structures. We draw on these results to explore all stages of the bridges' lifespan, from the initial design, through to long-term maintenance and asset management. The data and methods chosen are illustrated in Fig. 2 and described in the following sections. The assessment is set out in three distinct, sequential stages: (i) inputs and pre-processing, (ii) modelling and post-processing, and (iii) assessment and outputs.

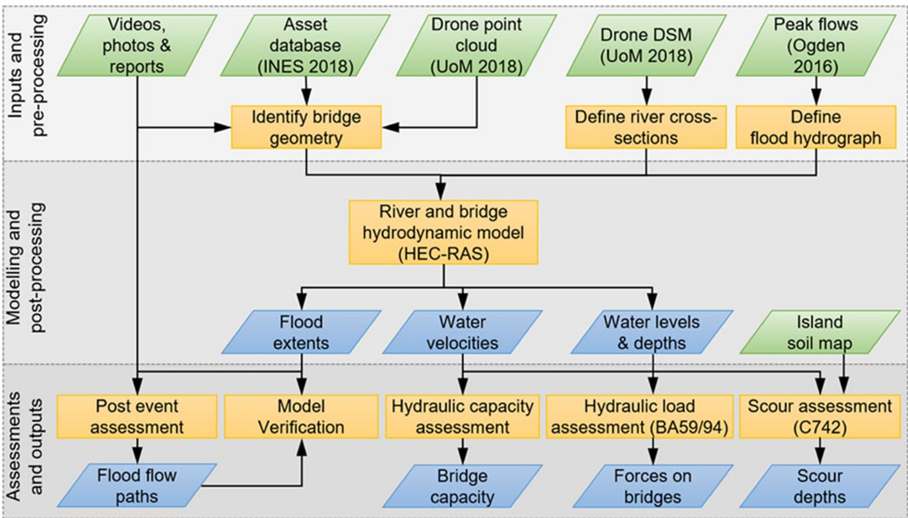

Fig. 2 Bridge assessment schematic, divided into three key stages. Note: University of Michigan DSM surveys are labelled as UoM 2018 (Zekkos et al. 2018)

3.1 Hydraulic modelling

The study river catchments (Table 1) can be divided into two groups based on their catchment area: (i) larger catchments (area > 20km^2)—Melville Hall, Roseau, Geneva Grand Bay, and Belfast; and (ii) smaller catchments (area < 10km^2)—Coulibistrie, Dublanc, Colihaut, Checkhall, and Pichelin. Most of the catchments have their headwaters in the steep interior of the island and the elevation drops to the coast (sea level) over a relatively short distance, resulting in very steep energetic river systems and extreme hydraulics (Fig. 1c).

The reach lengths modelled ranged from 630 to 2700 m (Table 1). All nine river reaches (Fig. 3) are single river channels, except for Pichelin, which is located at the confluence of two tributaries. The channel width of the reaches (Table 1) can be divided into two groups: (i) narrow, where the channel width is < 20 m (6 out of 9 reaches); and (ii) wide, width range 20–45 m (Melville Hall, Roseau, Geneva Grand Bay). Many of the reaches have either residential properties or a mixture of residential and commercial properties on either side and also upstream and downstream of the bridges. The exception is Melville Hall, where apart from the airport infrastructure on the left bank (North side), the river reach does not include significant residential areas. All residential areas are located on alluvial fans, where the gradient of the streambed shallows out, which encourages sedimentation of the river channels.

Following tropical storm Erika, a peak flow assessment was carried out for 16 river catchments in Dominica (Ogden 2016). Peak flood flows for the reaches range from 309 to 1500 m^3/s, representing a specific flow per unit area of 33 to 168 m^3/s per km^2. These are significantly large flows for such small catchments and illustrate the extreme nature of the hydrology in these hurricane events. The slopes of the river reaches vary between 1.45 and 4.6% and are strongly correlated with the catchment area, whereby reaches with larger catchments have lower river bed slopes. This relationship is well described with a power law relationship (Fig. 4).

For the hydraulic river modelling, structure from motion drone surveys were carried out for each river reach to derive very high-resolution (centimetric) digital surface models (DSM) by the University of Michigan (Zekkos et al. 2018), labelled as UoM 2018 in Fig. 2. We used the peak flows from Ogden (2016) as the hydrological inputs to the hydraulic modelling. A traditional one-dimensional hydraulic model of each river reach was built using HEC-RAS (v5.03) and cross sections extracted from the drone topography data (DSM). For the purposes of this study, the river reach is defined as the length of river channel and its floodplain where the bridges of interest are located and covers a suitable distance upstream and downstream of the bridges to ensure a proper understanding of the bridge context. The models included the river channel, floodplain, and bridge structures. The hydraulic models were run hydrodynamically to assess the hydraulic capacity of the bridge through a wide range of flows, from low to peak flood flows by using a synthetic triangular ramped hydrograph; see boundary conditions in Table 1.

3.2 Engineering assessment

The geometry of the bridge structures and other details of construction were taken from the innovative national asset database (INES 2018) and supplemented, where necessary, using dimensions scaled from photos of the bridges or measured from the drone point cloud data. All 19 bridges (Table 2) were included in the river modelling to account for their effects

Table 1 River reach details, ranked by catchment area from largest to smallest

Reach	Bridges*	River width (m)	Reach length (m)	Slope (%)	Catchment area (km^2)	Peak river flow (m^3/s)	Catchment characteristics
Melville Hall	1	30–40	2,700	1.70%	39.49	1,333	Second largest on island (after Layou River) & wider than most catchments
Roseau	4	20–40	740	1.57%	33.00	1,500	Steep & wide in the upper reaches
Geneva Grand Bay	1	35–45	950	1.80%	22.80	1,250	Wide with multiple tributaries, all are steep in the upper parts
Belfast	2	18–25	1,600	1.45%	21.84	1,320	Steep & wide in upper reaches
Coulibistrie	1 (1)	10–20	700	4.00%	8.13	900	Steep, long, and narrow
Dublanc	3	12–18	800	3.32%	7.67	377	Steep and narrow
Colihaut	1 (2)	8–12	1,200	3.30%	6.86	423	Steep, long, and narrow
Checkhall	1	18–20	740	3.85%	6.20	309	Steep, long and narrow
Pichelin	2	8–10	630	4.60%	3.09	519	Wide with multiple tributaries, all steep in the upper catchment

*Number of major bridges (number of minor bridges in brackets). Minor bridge not included in hydraulic modelling

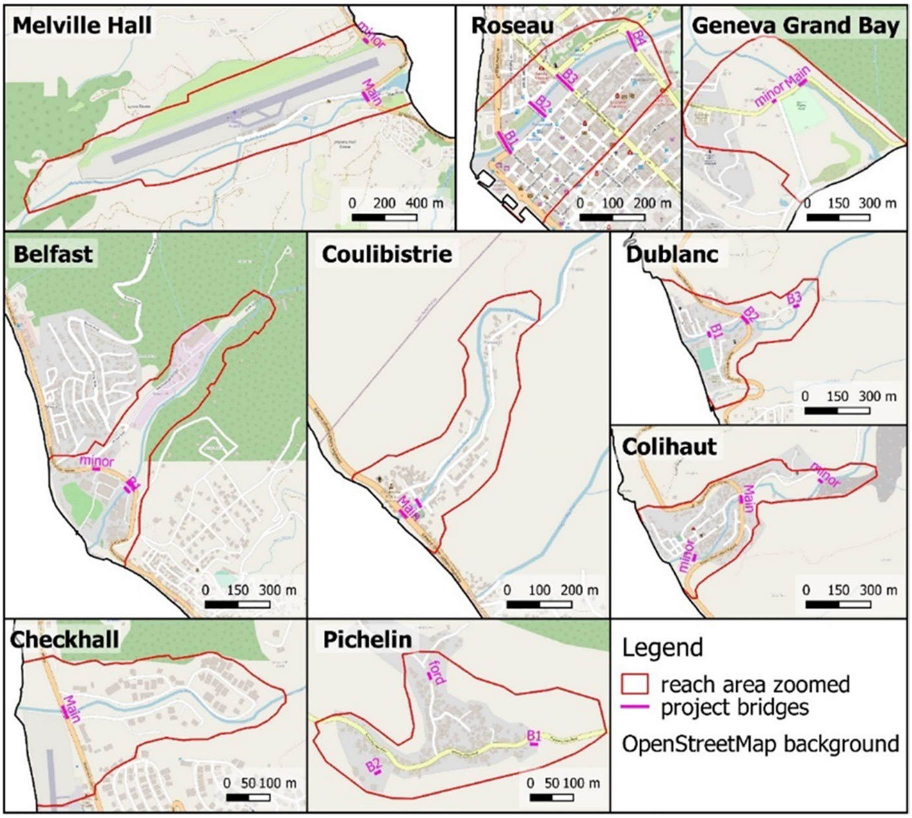

Fig. 3 All nine river reaches and the 19 bridges in this study (locations and catchments shown in Fig. 1c)

Fig. 4 Relationship between reach slope and catchment area for bridges

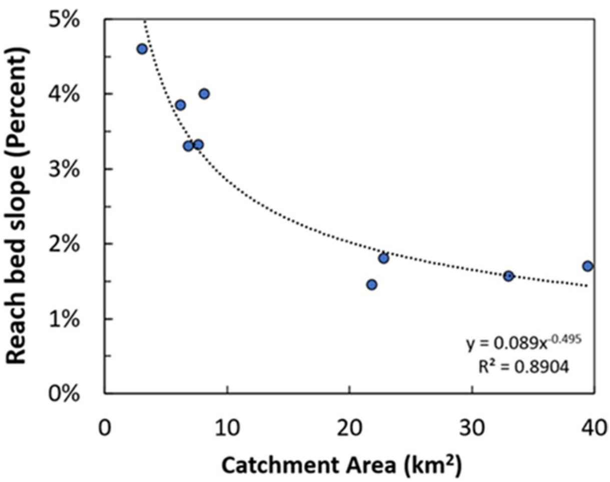

Table 2 Bridge structure summary for all bridges assessed

Study reach	Name	INES Asset ID	Type	Span (m)	Piers	Open flow area (m^2)
Melville Hall	Main	M3-SA-B-4322	Bridge	34.0	2 rectangular	89.0
Roseau	B1	M1-SG-B-15	Bridge	64.5	3 twin circular	98.6
	B2	U1-Roseau-58-B-1	Bridge	54.5	2 rectangular	162.0
	B3	U1-Roseau-54-B-207	Bridge	54.0	2 rectangular	177.0
	B4	M1-SG-B-Roseau-New-003	Bridge	51.0	2 rectangular	68.2
Geneva Grand Bay	Main	M7-SPK-B-5716	Bridge	33.0	No piers	87.0
Belfast	B1	No asset ID (minor)	Bridge	17.0	No piers	50.0
	B2	M1-SPl-B-5009	Bridge	21.0	No piers	91.3
Coulibistrie	Main	M1-SJH-B-9149	Bridge	18.0	1 rectangular	20.8
Dublanc	B1	U1-Dublanc-01-B-2	Bridge	9.0	1 rectangular	19.3
	B2	M1-SPR-B-Dublanc-New-004	Culvert	10.0	2 culvert walls	27.0
	B3	U1-Dublanc-04-B-281	Bridge	6.0	No piers	12.0
Colihaut	Main	M1-SPR-B-2811	Bridge	12.0	No piers	28.5
Checkhall	Main	M1-SPL-B-2793	Bridge	22.0	Single central	22.6
Pichelin	B1—Main	M7-SPK-B-3576	Culvert	5.0	No piers	7.6
	B2—Minor	F7-SPK-B-Geneva-New-002	Culvert	5.0	Single central	10.5

on river hydraulics. However, 3 bridges were considered very minor and were excluded from the subsequent detailed hydraulic load and scour analysis. Of the 16 bridges that were analysed, 10 have an overall span greater than 17 m, representing the wider urban bridges, such as Roseau's four urban bridges (Fig. 5). The remaining 6 bridges analysed have an overall span of less than 12 m (Fig. 6). Three of these smaller bridges are actually large box culverts. For the island of Dominica, the majority of the bridges have a span less than 10 m, so these smaller span bridges are generally more representative of the majority of bridges on the island.

Standard engineering calculations are used by engineers to assess the forces and other effects, such as scour, on structures (in this case, bridges). They generally follow an agreed standard and provide a consistent, repeatable method to assess the effect of complex

Fig. 5 Roseau Bridges 1, 2, 3 post Hurricane Maria. Left hand side of photo is downstream. Source: 4:03 min, https://www.youtube.com/watch?time_continue=8&v=_BlP5A3gTIo

Fig. 6 Example of the smaller bridges, Colihaut main bridge (a) from left bank downstream, and (b) from drone orthophoto

environmental conditions on a structure. Water velocity and depth outputs from the hydraulic model were used to undertake standard engineering procedures to calculate bridge loads: hydrostatic, hydrodynamic, and debris impact loads BA59/94 (HE 1994, 2012), and for scour depth calculations using C742 (Kirby et al. 2015). The bridge geometry provides the calculated area exposed to the depth of the flood water and river velocity provides the input to the calculation of dynamic forces on the bridge and the potential depth of the erosion of the river bed under the bridge (scour).

3.3 Model and process verification

An extensive search was made for visual and written material that document the two recent extreme events (Erika and Maria). These included post event assessment reports carried out by the Government of Dominica, as well as consultants' reports on bridge structure conditions. Freely available high-resolution satellite photos before the event (via Google Earth) and taken specifically just after Maria were also used. Social media also provided a rich source of images and videos specifically related to the events, identified using a systematic keyword search using the names of the towns in each catchment, hurricane or storm, and bridge. Of particular importance were a series of drone flyover videos filmed by local residents and made available through YouTube.

The collated information was used to identify physical processes which occurred for each river system and bridge during these extreme events. These processes are location specific and were critical in understanding how the flood events unfolded, as they progress dynamically through different stages. Documenting and assessing these physical processes was therefore critical for understanding the resilience of infrastructure in and around the river channel. The aim of this post event forensic assessment was to use all the evidence to reconstruct the temporal and spatial detail of what occurred during the event. This information also provided a verification of the modelling work, especially given the lack of flow data to calibrate the models and the uncertainty in the hydrology. Please see the supplementary information for more detail on the methodologies and datasets used as well as definitions of the relevant physical processes documented.

4 Results

4.1 Hydraulic capacity

From the hydraulic assessment, the capacity of all the bridges is insufficient to pass the peak flow expected from the hydrology assessment, with a mean for all 16 bridges of only 21% of the peak flow passing safely through the bridge opening without overtopping/bypassing (Fig. 7a). It should be noted that international standards typically require sufficient hydraulic capacity to pass the 1 in 100 year (1% probability) to the 1 in 200 year (0.5% probability) flows for a river. Without long-term gauged flow data, it is difficult to determine a probability for the Erika and Maria events, which introduces significant uncertainty for designing bridges with sufficient capacity. In Dominica, the largest bridges have around a 50% capacity compared to the modelled flows. Some smaller bridges only have a 5–10% flow capacity.

When comparing hydraulic capacity, as a percentage of peak river flow, against the open area under a bridge (Fig. 7b), bigger bridges generally have larger relative capacities than smaller bridges. This may be due to the fact that larger bridges are more costly and may be designed more carefully, or to higher standards. Newer bridges on the island are generally being designed with larger capacities, e.g. Roseau B1, Roseau B2, and Melville Hall, but even these were insufficient in the face of Maria.

4.2 Bridge loads

The larger bridges experience greater forces, as they have larger structural elements that interact with the flood water (Fig. 8). The breakdown of individual forces show some interesting variations between bridges (Fig. 8a) and provides an explanation for why some bridges have high forces relative to their span (Fig. 8b). A solid parapet for Roseau B4 increases almost all the forces experienced by the bridge. Melville Hall also has a solid parapet which ties in with a flood defence wall on the left bank upstream protecting the

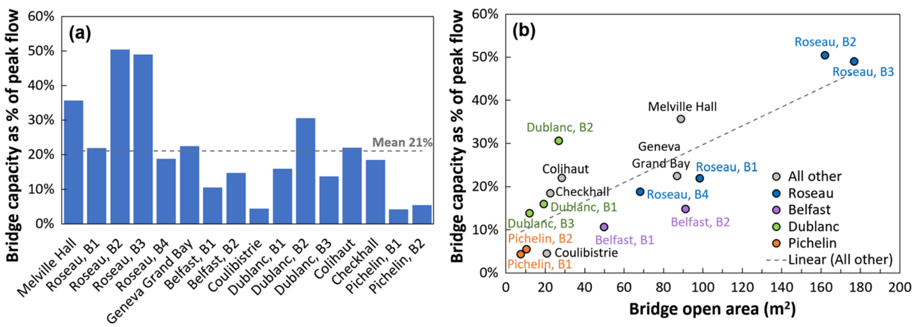

Fig. 7 Bridge capacity, (a) expressed as a percentage of peak river flow, and (b) compared to open area under the bridge

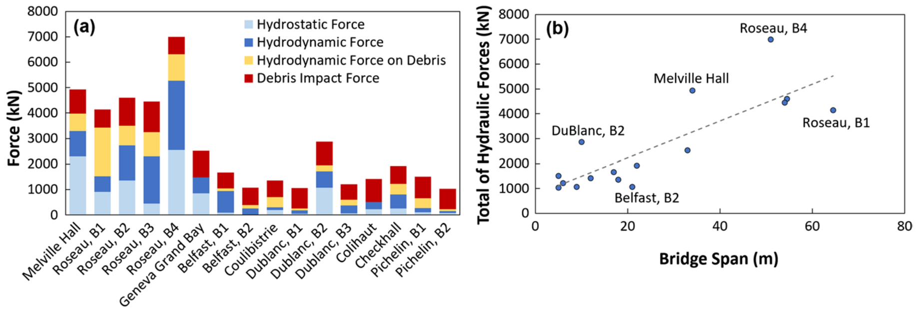

Fig. 8 Hydraulic forces: (a) breakdown on all bridges, (b) total hydraulic forces relative to bridge span

airport, allowing the bridge to surcharge and increases hydraulic capacity as a result (Fig. 7b). Dublanc B2 is a culvert set in a high embankment, so can also experience high upstream water levels and therefore large forces.

Bridges in Belfast, Coulibistrie, and Pichelin experience relatively small forces, mainly due to the small hydraulic capacity of these bridges and their upstream river channel/bank arrangements that allow most of the flood flows to freely bypass the bridges. Those bridges without piers, such as at Geneva Grand Bay and Colihaut, experience no forces resulting from debris trapped on the piers. Larger bridges with multiple piers show proportionally increased forces. There are bridges with no piers (Belfast B1 and B2, Pichelin B1, and Dublanc B3), but that have abutments that protrude into the channel and provide an effective width to trap debris. With smaller bridges, the debris impact force represents an increasing proportion of the total load, as this is related to the water velocity rather than the structure size. Smaller bridges are also located on steeper reaches (Fig. 4) which experience higher flow velocities, increasing the impact force.

4.3 Local scour

Scour is expressed as the potential depth of bed material removed and if this depth is sufficient to undermine structural elements of the bridge, it can cause the collapse of the bridge. Scour is commonly classified into various types, with definitions in the literature varying widely. Here, we consider local scour, defined by C742 (Kirby et al. 2015) as scour associated with particular local features that obstruct and deviate the flow. More specifically, we consider local scour at two locations: local bridge pier scour and local channel scour in the area adjacent to riverbank revetment. For the study bridges, scour values vary from 0.41 to 3.87 m (Fig. 9). These represent the maximum values experienced throughout the modelled flood event. Channel scour is shown to be highly influenced by the geotechnical properties of the riverbed. For Dominica, this results in calculations giving a wide range of scour depth values (lower and higher rates in Fig. 9) due to lack of local data and understanding of the variation of grain sizes.

For Dublanc (B2), scour represents potentially the greatest risk mainly because of the water retention behind the raised road embankment which generates high velocity flow through the culverts, which is then capable of causing deep scour downstream of the culvert outlets. This occurred previously at this structure, and it was recently repaired in 2016. The structure is also potentially more vulnerable to scour because the culverts are unlikely

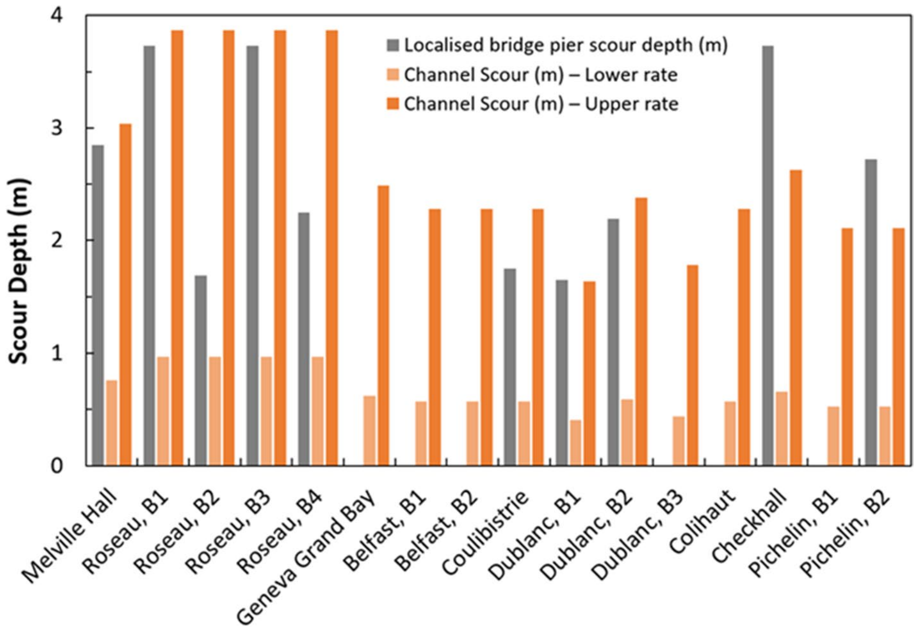

Fig. 9 Scour depths for bridge piers and river channel adjacent to riverbank protection

to have the deep, scour-resilient foundations that bridge abutments and piers usually have as part of their design. Pier scour was also computed for this structure, the central dividing walls between the culvert barrels being classed a bridge pier of sorts, but these piers are not vulnerable to scour provided the erosion-resistant culvert base slabs remain intact.

Bailey bridges, like the one at Geneva Grand Bay, consist of truss structures that form a semi-impermeable barrier when blinded (blocked) with debris, and cause large depths of water to back up behind the bridge. This generates high velocities through the bridge and subjects the bridge to large hydrostatic forces. There are many examples of bailey bridges failing within a few years of their installation, usually due to scour of abutments, as was the case for Geneva Grand Bay.

4.4 Physical processes during hurricane events

The post event assessment provided significant evidence for the main physical processes related to the river and bridge structures during the hurricane flood event, namely avulsion, bypass flow, debris accumulation, sediment deposition, and scour; some of which are illustrated in Fig. 10, and defined in the supplementary material to this paper.

Where there is clear evidence of these processes for each reach and bridge, we have documented this (Table 3). Note that the table only shows where there is clear evidence of the process, rather than that it did not occur, as we are limited by the collated photos, reports, and videos. Multiple physical processes also commonly occur together in the same flood event on a specific reach and may represent higher risks to structures on those reaches. Bridges at Coulibistrie and Roseau illustrate some of these processes, as shown in Fig. 10.

Fig. 10 Post Maria damage in (left) Coulibistrie Reach showing bypass flows and debris build up, (right) Local bridge scour exacerbated by debris at Roseau Bridge 3

Table 3 Study reaches and bridges with clear evidence of a specific physical process occurring during Erika or Maria

Study reach	Name	Avulsion	Bypass flow	Debris	Sediment	Scour
Melville Hall	Main	-	Yes	-	-	-
Roseau	B1	-	Yes	Yes	-	-
	B2	-	Yes	Yes	-	-
	B3	-	Yes	Yes	-	-
	B4	-	Yes	Yes	Yes	-
Geneva Grand Bay	Main	Yes	Yes	Yes	-	-
Belfast	B1	-	Yes	-	-	-
	B2	-	Yes	-	-	Yes
Coulibistrie	Main	Yes	Yes	Yes	Yes	-
Dublanc	B1	-	Yes	-	Yes	-
	B2	-	Yes	-	-	-
	B3	-	Yes	-	-	-
Colihaut	Main	Yes	Yes	-	Yes	-
Checkhall	Main	-	Yes	-	Yes	-
Pichelin	B1—Main	Yes	Yes	Yes	Yes	Yes
	B2—Minor	-	Yes	Yes	-	-

When we synthesise the results of the multiple analysis approaches we have used, we begin to see the range of water-related hazards that the bridges are exposed to, and their relative magnitudes (Table 4). Although there are commonalities due to the extreme nature of the event, the specificities of each bridge and its unique context result in a more holistic view of these complex systems, where infrastructure and a dynamic environment interface.

5 Discussion

It is clear that bridges in Dominica are subject to extraordinarily extreme hydraulic conditions during hurricanes and tropical storms. Combining this with the steep terrain results in high energy river systems and multiple flood flow processes that affect the bridge integrity.

Table 4 Synthesis results of analyses for bridges and their catchments

Study reach	Bridge name	Catchment area (km^2)	River slope	Bridge span (m)	Bridge capacity (% Erika)	Total load (kN)	Scour, pier, and channel (m)	Evidenced processes
Melville Hall	Main	39.5	1.70%	34.0	35.6%	4929	2.85, 0.76–3.04	Bypass
Roseau	B1	33.0	1.57%	64.5	21.9%	4144	3.73, 0.97–3.87	Bypass, debris
	B2	33.0	1.80%	54.5	50.4%	4604	1.69, 0.97–3.87	Bypass, debris
	B3	33.0	1.45%	54.0	49.0%	4446	3.73, 0.97–3.87	Bypass, debris
	B4	33.0	4.00%	51.0	18.8%	6991	2.25, 0.97–3.87	Bypass, debris, sediment
Geneva Grand Bay	Main	22.8	3.32%	33.0	22.4%	2521	n/a, 0.62–2.49	Avulsion, bypass, debris
Belfast	B1	21.8	3.30%	17.0	10.6%	1665	n/a, 0.57–2.28	Bypass
	B2	21.8	3.85%	21.0	14.8%	1069	n/a, 0.57–2.28	Bypass, scour
Coulibistrie	Main	8.1	4.60%	18.0	4.4%	1354	1.75, 0.57–2.28	Avulsion, bypass, debris, sediment
Dublanc	B1	7.7	1.70%	9.0	15.9%	1060	1.65, 0.41–1.64	Bypass, sediment
	B2	7.7	1.57%	10.0	30.5%	2869	2.19, 0.59–2.38	Bypass
	B3	7.7	1.80%	6.0	13.8%	1214	n/a, 0.44–1.78	Bypass
Colihaut	Main	6.9	1.45%	12.0	22.0%	1417	n/a, 0.57–2.28	Avulsion, bypass, sediment
Checkhall	Main	6.2	4.00%	22.0	18.4%	1924	3.73, 0.66–2.63	Bypass, sediment
Pichelin	B1—Main	3.1	3.32%	5.0	4.2%	1504	n/a, 0.53–2.11	Avulsion, bypass, debris, sediment, scour
	B2—Minor	3.1	3.30%	5.0	5.4%	1034	2.72, 0.53–2.11	Bypass, debris

Our results document these physical processes and quantify the magnitude of the effects. These processes are also reported in other bridge studies under similar physical extremes, such as for Fiji (Amir-Ansari 2013) and Queensland, Australia (Pritchard 2013).

Even with the huge uncertainty in river flows used in the modelling, it is clear from the processes documented in the event that the actual river flows are very extreme. It is also clear that sediment and floating debris are important factors in changing channel and bridge capacity during the events. While newer bridges have larger relative capacities, these are still insufficient, if the aim is to build bridges bigger than design flows. Partly due to the insufficient hydraulic capacities of the bridge, but also related to the natural geomorphological processes evident during these events, bypass flows are always evident and cause significant damage in the settlements alongside the river and road infrastructure.

For all the reaches, the hydraulic conditions in the river channels are supercritical or approaching supercritical under high flows. This means water velocities are very high, and therefore hydrodynamic forces and scour are significant. Despite many of the bridges being located where the river slope shallows out onto the alluvial fans next to the coast, they are still relatively steep, especially compared to many rivers in other countries, and importantly steeper than usually allowed for in international design standards. Noticeably from the hydraulic modelling, and corroborated by the photo evidence, there are a few locations within the reaches where conditions sometimes transit to subcritical. This is usually due to a structure causing afflux and lowering velocities sufficiently to move conditions from supercritical to subcritical (with an associated hydraulic jump). This reduces the river's ability (capacity) to carry sediment, which is always significant in Dominica, such that any sediment load is deposited at that location, commonly under or in front of the bridges, further reducing the hydraulic capacity of the bridge or channel.

Bridge structures are calculated to experience large loads during flood events due to hydraulic action. These combined loads can lead to the failure of weak bridge structures or components. Bridge design and detailing are important in terms of the forces experienced by a particular bridge structure. For example, the solid parapet on Roseau B4 increases almost all the forces on the bridge, resulting in the highest total load of all the bridges studied.

Channel change, scour, and deposition represent significant risks to the bridge structures in Dominica. The erosion of the road embankment during its overtopping by bypass flows is also a major risk and is generally not accounted for in the design of structures, and this is confirmed by the post Maria analysis. If this embankment erosion occurs close to the bridge, it can undermine the abutments and cause bridge failure. Embankment failure can result in a sudden release of a relatively large volume of water and debris downstream and is a potential consequence of channel scour or embankment overtopping erosion. The risk of this occurring will depend on the composition of the road embankment and any erosion protection measures that exist on the embankment and at the culvert outlets.

The quantity of sediment present in high river flows in Dominica is significant and sediment dynamics modifies the river channel significantly during the flood events. This is one of the most difficult aspects to build into design and modelling methodologies and is currently poorly implemented in bridge design, both in Dominica and more generally. In part, this is due to the standard methods and tools being unable to take this into account, but also due to the uncertainty in the quantities and distribution of sediment loads and bed material being very uncertain, as there are very few data (and studies) for these aspects.

There is strong evidence that landslide dams occur upstream of bridges during flood events in the Dominica catchments, as implied by the differences between hydrology modelling and indirect measurement of peak flows. When these temporary dams breach, they may result in peak flows ~ 3–4 times higher (possibly more) than normally expected as a peak flow in the river (Ogden 2016). This significant increase in flow, sediment, and debris causes significant problems for downstream structures and communities and are not currently included in design considerations.

The findings of this study have specific implications for bridge design and management in Dominica and similar SIDS contexts, as well as perhaps further afield. Understanding the challenges can lead to practical strategies for improving resilience. Our approach recognises that bridges and their contexts can be considered systems in their own right and act as a critical interface connecting infrastructure networks, river networks, and their catchments, as well as the communities they serve. Therefore, our system synthesis and prognostic approach (Chen 1975) provide a pragmatic and holistic way to approach the challenge of bridge resilience that goes beyond a singular design problem. A system understanding can be a powerful way of understanding and improving resilience in natural hazards (Harrison and Williams 2016).

Unsurprisingly with complex systems' challenges, such as is the case here, there is no single solution. Capital budgets, as well as logistical and supply limitations, mean that building bridges that would be big enough to avoid most of the physical processes evident is just not feasible in the SIDS context. In addition, it is clear from the study results that even with the more recently constructed bridges, many of the common design practices that would be expected to ensure resilient design to extreme conditions have not been considered, or perhaps the conditions have been severely underestimated (possibly due to data limitations). There are many methods and approaches to improving bridge design and resilience that have been applied successfully in different contexts over the years. We explored and collated these and selected those that were most applicable and practical in the SIDS context and importantly, specifically addressed the physical processes evidenced in this study (see Table 4) and the issues identified in the assessment results.

We make 26 specific resilience mitigation measures based on this study (Table 5) and suggest all of these are applied to assessing existing bridges and new builds. These recommendations are grouped by *type*, *issue*, *and scale*. The *type* of measure grouping refers to the basic form of measure, such as attention to design details, improvements to design methods, and specific additional mitigation structures. The *issue* grouping relates to what specific physical challenge the measure is addressing, for example, extreme hydraulics, bridge capacity limitations, or forces on the bridge structure. Finally, *scale* refers to the scale of application of the measure, divided into structure, reach, and catchment scales. At the core of these recommendations, we find that there are reoccurring underlying issues that need to be addressed to move resilience improvements forward in the future.

Data and information to feed into the design process are generally hard to find and present a significant challenge to designers in creating resilient structures. While some information is available from limited previous studies, there is no systematic collection of long-term data to assist with probability analysis, for example. This leads to large uncertainties in parameters for design. However, long-term hydromet networks are challenging to maintain in the face of such extreme events.

New methods are providing interesting low-cost alternatives to collecting data, such as digital elevation models through drone survey (Schaefer et al. 2020). However, from our own experience, these can bring new challenges in terms of locally resourcing the application of these methods and integrating the resulting data in existing design and assessment methodologies. This study used social media content of islanders' experiences of the event, with drone videos and photos, which provided a rich record to draw from. Additional opportunities arise

Table 5 Specific bridge resilience recommendations for Dominica

No	Recommendation	Description	Type[a]	Issue[b]	Scale[c]
1	Knowledge of local conditions	Designers should be familiar with extreme hydraulic conditions	DM	EH	S/R/C
2	Appropriate river modelling	Undertake mixed regime hydrodynamic full shallow water river modelling (not steady state)	DM	EH	S/R
3	Account for hydrological uncertainty	Use a check event scenario during modelling to allow for hydrological uncertainty	DM	EH	S/R/C
4	Velocity change checks	Carry out explicit checks for velocity changes that could cause sediment deposition	DM	EH	S/R
5	Blockage checks	Use a blockage scenario to understand what might happen during bridge blockage	DM	C	S/R
6	River dredging	Channel dredging after events to maintain capacity	RRM	C	S/R
7	Streamlined design	Overall bridge design to reduce afflux and blockage risks to lower forces and lower magnitudes of bypass flows. See also 8, 9, 10	DD	C/B/F	S
8	Pier considerations	Correct spacing of and reduce number of piers. Solid piers shaped for flow and to reduce debris collection	DD	C/F	S
9	Abutment considerations	Avoid abutments that constrict the river and protect them from scour – especially below river bends	DD	C/F	S
10	Deck considerations	Protect from floating debris impact if vulnerable and reduce forces where possible	DD	C/F	S
11	Design for bypass flow	Design bridges and surrounding infrastructure assuming bypass flow will occur and manage this	DM	B	S/R
12	Include communities	Include consultation with communities where bypass flows are managed to provide integrated solution and reduce risk through knowledge	DM	B	S/R
13	River momentum protection	Effect of bends needs to be considered explicitly in the design, for example, increase rip-rap protection on appropriate side of river after bends	DD	EH	S/R
14	Freeboard for floating debris	Increased clearance to allow for floating debris to pass under bridge	DD	F/D	S
15	Debris shields/ deflectors	Consider debris shields to protect bridge structure from impact of floating debris where elements are vulnerable (e.g. span members)	DD	F/D	S
16	Specify detachable parapets	Detachable parapet railings to reduce forces on bridge and debris trapping problems	DD	F/D	S
17	Intercept floating debris	Intercept and collect woody debris before it reaches the bridge, e.g. sweepers, sacrificial piles, ramps, collection basins, debris catchers	MS	F/D	R
18	Debris removal	Regular and emergency removal of debris at bridges	RRM	F	R
19	Riverbed protection	Consider bed protection approaching the bridge and after the bridge to reduce scour	DD	S	R
20	Sediment grain size survey	Bed grain size surveys to reduce uncertainty in design for scour	DM	S	R
21	Improved rainfall and flow measurement	Hydrometeorological monitoring on the island to reduce uncertainty in flow design probabilities and magnitude	DM	EH	R/C

Table 5 (continued)

No	Recommendation	Description	Type[a]	Issue[b]	Scale[c]
22	Landslide dam risk factors	Identify factors that increase risks of landslide dams upstream	RCM	LD	C
23	Catchment stabilisation	Catchment management through tree planting and slope stabilisation	RCM	LD	C
24	Migrating river bends	Identify river bends at risk of migration and with the potential to cause landslide dams and install bank protection there	RCM	LD	C
25	Road induced landslide dams	Careful design of roads with the possibility of inducing landslide dam formation	RCM	LD	C
26	Landslide dam event check	Design of bridges should include a scenario for 3 times peak flow to see what may happen	DM	LD	S/R/C

[a]Type: *DD* design details, *DM* design methods, *MS* mitigation structures, *RRM* river reach management, *RCM* river catchment management

[b]Issue addressed: *EH* extreme hydraulics, *C* bridge hydraulic capacity, *F* forces on bridges, *B* bypass flows, *D* floating debris, *S* scour, *LD* landslide dams

[c]Scale: *S* structure, *R* reach, *C* catchment

from the deployment of inexpensive wireless sensors that can be used to collect data (such as precipitation and flow) at a significantly lower cost than previously possible.

The lack of specific design standards for the island can lead to an inconsistency of approach and the potential to overlook context specific issues. It should also be noted that there are acknowledged deficiencies in international standards, for example, in terms of learning from recent extremes (Pritchard 2013) and with regard to multi-hazard design and analysis of bridges and highway infrastructures (Banerjee et al. 2019) and that these are particularly important in the SIDS context (López-Marrero et al. 2013).

The lack of fundamental research in the SIDS context leaves many gaps in our understanding of the factors that affect bridge and infrastructure resilience, making it challenging for designers and managers to know how to mitigate current hazards, as well as possibly more extreme conditions in the future due to climate change. While research from other contexts may well be usefully applied to SIDS, these methods developed elsewhere often rely on a level of data that is generally unavailable in SIDS. Therefore, the application of complex, data hungry, and sometimes overly academic methodologies from a developed country context to the SIDS context is not the answer, due to data limitations, resource capacity, and physical and climate context differences. Specific, locally relevant research, drawing on the experience of those professionals on the islands that manage the infrastructure on a daily basis, needs to take place to advance our understanding of the issues.

Staff at the Ministry of Public Works (MOPW) in Dominica shared many photos and documents that fed into this research. Nonetheless, it was still difficult to obtain structural details in the form of drawings or systematic asset records. As part of the wider resilience project on the island, an infrastructure asset database was established (INES 2018) and formed a key input dataset for this bridge assessment study. Maintaining this database and using it to manage risks and prioritise mitigation will be crucial to ongoing resilience. It could also form a repository of hurricane impacts on bridges, as well as the cost and effectiveness of the proposed mitigation strategies, for future adaptation of strategies based on experience. This information can be used to prioritise limited maintenance funding and understand implications for the wider road network of a specific bridge failing (Dehghani et al. 2014).

The effect of floods, specifically bypass flows, on the communities adjacent to the rivers and bridges requires further attention as part of the asset design and management processes. Better integration and inclusion of the communities in this design process can often lead to enhanced resilience, both of the structure and the adjacent community, through enhanced awareness of risks as well as the direct inclusion of experience of past events into the design process. Beckford (2018) argues that sharing traditional experiential knowledge across the communities and islands is an invaluable resource and cultural capital in the Caribbean that is largely untapped at the moment in the top-down approaches to climate resilience.

Finally, while the multiple method analysis results can help identify specific mitigation actions that can be taken for individual bridges, it also points to the future possibility of creating a measure of compound risk to the bridges which quantifies and sums the parameters related to each of the hazard components, without necessarily undertaking the level of analysis detail we have applied here.

6 Conclusions

We have demonstrated that it is possible to carry out a comprehensive assessment of bridge infrastructure resilience through the integration of readily available data, methods, and post disaster forensics, despite the many challenges faced in a SIDS context. Through this holistic systems approach, even limitations on the availability of data and tools do not impede addressing resilience issues, nor are complex academic approaches required to identify practical measures to increase resilience of existing and new infrastructure. While there are a growing number of studies exploring forensic disaster investigation and systems thinking, to our knowledge, this paper is the first to systematically explore bridge resilience in the SIDS context.

This study focuses on extreme events driven by hurricanes and tropical storms in a SIDS context. In this regard, the event magnitudes are typically beyond that envisaged by international design codes, and the research underpinning them, that are applied on the islands. It is therefore important to adapt engineering standards used to the local SIDS context carefully and appropriately. More research is also required to enhance engineering design and assessment standards, both to allow their application in data scarce contexts, but also to encompass the effects of climate change, beyond just bigger events. These lessons apply to the global infrastructure context, as SIDS can be considered on the front line when it comes to the impact of climate change that will be felt in the future.

Although financial and other constraints mean that building ever larger bridges may not be feasible, there are still practical, relatively inexpensive measures that can be taken to improve resilience for both new and existing structures. The challenge is both for bridge designers to build smarter infrastructure, but also for asset managers to be aware of changing conditions the infrastructure is exposed to and improved monitoring and assessment of existing assets.

Adapting and using new technology, such as drones to fill data gaps, shows significant promise in terms of cost and speed. However, it is also necessary to adapt traditional design and modelling methods to utilise this new form of data and there is still further development required in streamlining the use of these new methods with existing engineering standards. There is still a requirement to invest in long term data collection and sharing.

International and local consultants have a responsibility to examine their design methods' applicability to the SIDS context and share results/findings for future designs and studies to learn from. We encourage open publication of findings and sharing of reports. Datasets from this work, for example, can be found shared on the open access Dominica Geonode (Dominode: https://dominode.dm/). Collection of long-term data locally by SIDS authorities for parameters such as river flow and rainfall will also aid in increasing future resilience of infrastructure.

Modelling methods typically used in SIDS contexts by consultants need to improve to include sediment dynamics and geomorphological change. A consequence of this would be a requirement for even more data, potentially more uncertainty in results, as well as requiring a higher technical skill level for their application. So, this on its own would not be the whole solution and more complex models therefore also need to be easier to apply, to avoid undermining local capacity building within the SIDS context.

Bridge designers should acknowledge the extreme nature and uncertainty in design parameters and move to a broader and smarter assessment of risk for a bridge design. This will mean moving away from just modelling one design level scenario, but instead assessing a wider range of event scenarios and being more aware of the environmental context of the structures. It also means adapting international standards where necessary, rather than carrying out a minimum application approach.

For the design of new structures, or mitigation modifications carried out on existing structures, terms of reference should require explicit attention to the SIDS specific challenges to ensure consultants are both aware of, and adjust to, local conditions. In addition, engagement with affected communities and their inclusion as stakeholders in the design process may not only yield a more holistic solution, but will also raise public awareness of the potential impacts on their community, increasing the preparedness and resilience of the community.

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Data availability Geospatial datasets from this paper can be found shared on the open access Dominica Geonode (Dominode: https://dominode.dm/), as well as directly from the corresponding author.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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