Policy Research Working Paper 9190

Estimating Resiliency Benefits of Road Upgradation

Case of the East Road in Malaita, Solomon Islands

Darwin Marcelo
Aditi Raina

WORLD BANK GROUP
Infrastructure, PPPs & Guarantees Global Practice
March 2020

Abstract

Governments and their multilateral partners are increasingly recognizing the importance of incorporating climate and disaster resilience considerations into infrastructure development plans as well as the related construction and financing decisions. The potential medium- and long-term benefits of increased resilience must be considered alongside short-term costs of resilient design and implementation. The objective of this paper to estimate the resiliency benefits, in terms of key socioeconomic outcomes, under several road upgradation options and rainfall scenarios. The estimated benefits are compared against the related lifecycle costs to inform investment decisions. The analysis is based on the methodology developed by the World Bank and Kyoto University to operationalize and measure key infrastructure resilience concepts at the project level. The East Road in Malaita in the Solomon Islands is used to pilot the this methodology and examine its applicability. The parameters selected to measure resiliency are based on the key benefits the road provides to the people living around it: economic benefits proxied by travel time, access to hospitals, and access to markets. Due to data constraints in Malaita, the report is based primarily on expert inputs and geo-spatial data. It considers mainly technical improvements to road upgradation that might impact resiliency.

This paper is a product of the Infrastructure, PPPs & Guarantees Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at dmarcelo@worldbank.org and araina1@worldbank.org.

Produced by the Research Support Team

Estimating Resiliency Benefits of Road Upgradation:
Case of the East Road in Malaita, Solomon Islands

- Darwin Marcelo and Aditi Raina

Keywords: Infrastructure resilience, infrastructure prioritization, climate resilience, transport, resilient roads, quality infrastructure

JEL Classification Codes: R42, H54, O18, O21

Acknowledgements: This report was written by Darwin Marcelo (Senior Infrastructure Economist) and Aditi Raina (Infrastructure Analyst) and was supported by Hanqi Shi (GIS Consultant) and Schuyler House (Infrastructure Economics Consultant). Expert inputs were provided by Serge Cartier Van Dissel. The paper benefited from World Bank peer reviewers, including Christopher Bennett (Lead Transport Specialist, IEAT1), Stephanie H. Tam (Sr. Operations Officer, SSACD) and Julie Rozenberg (Senior Economist, SLCUR). Valuable comments were also received from Naoki Kakuta (Transport Specialist, IEAT1), Dung Anh Hoang (Senior Transport Specialist, IEAT1) and Guido Rarangwa (Representative, Solomon Islands). The team is grateful for support from Luis Tineo, Jared Phillip Mercadante and Michel Kerf. The World Bank's Infrastructure Finance, Public-Private Partnerships, and Guarantees Group (IPG) led this work with support from the Japan-World Bank Program for Mainstreaming Disaster Risk Management in Developing Countries through the Tokyo DRM Hub.

Contents

Estimating Resiliency Benefits of Road Upgradation: Case of the East Road in Malaita, Solomon Islands

I. Introduction

Infrastructure resilience may be characterized as the capacity to plan for and effectively respond to both short-term disaster shocks and long-term effects of climate change in a manner that minimizes service disruption and reduces the associated costs – financial, economic, environmental, and social – on society. Resilience capacity depends on the physical resistance of an infrastructure asset to natural hazards, as well as the processes in place to help facilitate safe and rapid recovery, and the safeguarding of financial and physical resources for effective response.

Due to the recognized economic and social impacts of natural disasters and climate change – perhaps most notably captured in the findings and recommendations of the Sendai Commission – resilience to natural disaster is a growing and prominent concern for infrastructure planners, governments, and citizens.[1] This is particularly true in areas vulnerable to extreme hydrometeorological and geophysical risks, such as floods, earthquakes, and major storms, as well as in areas where rising sea levels or altered weather patterns associated with climate change expose the region to significant vulnerabilities.

Meteorological and geophysical disasters have killed an estimated 1.3 million people between 1998 and 2017, and left an additional 4.4 billion people displaced, injured, or homeless. While fatalities were caused largely by geophysical events, 91% of disasters were caused by hydrometeorological events, including floods, storms, and other extreme weather events. These disasters have resulted in direct economic losses of US$2,908 billion, again largely accounted for by weather-related disasters, which accounted for 77% of total direct losses. Among low-income countries, reported hydrometeorological losses of US$21 billion amounted to an average of 1.8% of the GDP, well above the IMF's 0.5% threshold for a major economic disaster.[2] These impacts push an average 26 million people into poverty every year, overwhelmingly affecting already-vulnerable populations.[3]

The World Bank finds that costs are largely under-reported, and that real costs to the global economy amount to an approximate US$520 billion each year.[4] When the costs of medium-intensity but frequent hazards and the slow-onset effects of climate change are further considered in addition to costs associated with high-intensity events (e.g., earthquakes and typhoons), the economic and social impacts are often much higher than otherwise estimated. In the Asia-Pacific region, for example, average annual losses for high-intensity extreme events are US$14.89 billion. These costs rise to an approximate US$19.35 billion when also considering medium-intensity, frequent events, such as heavy rains, and US$27.1 billion if indirect costs are included. Considering the costs of slow-onset events, such as droughts, the average annual costs swell to an astounding US$675 billion.[5]

Costs of Disruption

The direct and indirect costs associated with disaster-related infrastructure damages are also staggering. Effects on households can be felt through many channels, including delayed health care provision,

---

[1] World Bank and PHRD (2012). The Sendai Report – Managing Disaster Risks for a Resilient Future. World Bank, Washington DC.

[2] CRED and UNISDR (2018). Economic Losses, Poverty & Disasters: 1998—2017.

[3] The World Bank (2017). Results Brief - Climate Insurance.
https://www.worldbank.org/en/results/2017/12/01/climate-insurance)disasters

[4] Ibid.

[5] UNESCAP (2019). The disaster riskscape across Asia-Pacific: Pathways for resilience, inclusion and empowerment. Asia-Pacific Disaster Report. United Nations Economic and Social Commission for Asia and the Pacific (ESCAP).

difficulties accessing food and other essential goods, price shocks affecting the economy, and disruptions to wages.[6] Hallegatte, Rentschler, and Rozenberg (2019) estimate that direct damages to power generation and transport in low- and middle-income countries cost US$18 billion a year. But these direct repair costs swell to much higher levels when considering the costs to firms and households associated with disrupted and unreliable service.[7] The authors estimate that, altogether, disruptions caused by natural hazards coupled with poor maintenance and mismanagement, cost households and firms reach US$390 billion each year in low- and middle-income countries. These include costs associated with direct impacts (e.g., greater congestion, time losses due to extended travel, and higher fuel costs); coping costs; and indirect impacts on public health, gender equality, as well as limitations on productivity and innovation.

Oblensky et al (2019) estimate that between 0.1% and 0.2% of GDP is lost each year due to unreliable electricity, water and transport infrastructure, due to adverse effects on firms and households. At the household level, infrastructure disruptions cause short-term missed work and education opportunities, costly inconveniences, and negative impacts on health. Households also experience long-term costs associated with mitigating the impact of disruptions or foregoing opportunities and valued activities due to lack of reliable service. These disruption costs are often underestimated, as they do not fully account for environmental costs and health impacts.[8]

Similarly, firms suffer significant productivity and utilization losses due to poor or unreliable service. Infrastructure provision is not enough to foster productivity unless it is reliable. Disruptions have significant adverse effects on firms due to disrupted supply chains, underutilization of production capacity, and costly adaptation measures.[9]

In the transport sector, assets are typically exposed to multiple hazards that compound the risks of asset failure and service disruption. In a global study of road and rail networks, Koks et al (2019) found that 27% of road and railway assets are exposed to at least one natural hazard and that 7.5% are exposed to a major hundred-year flood event. Expected annual damages to roads and rail due to natural hazards range from US$3.1 billion to US$22 billion, with most damages (73%) due to flooding. While the global annual expected damages are minimal with respect to annual maintenance costs, for countries with higher exposure levels to major floods – including Small Island Developing States – damages can reach catastrophic levels. In these countries, increased flood protection would have positive returns on about 60% of exposed roads and improved flood resistance is likely to be a low-regret investment in the context of climate change.[10]

Limao and Venebles (2001) estimate that poor maintenance and unreliable transport service accounts for 40% of transport cost for coastal countries and up to 60% for landlocked countries. Increased costs have significant impacts on the real costs of trade, often limiting a country's ability to participate fully in the global economy.[11] The monetary costs of infrastructure disruptions results in estimated utilization losses

---

[6] Obolensky, M., Erman, A., Rozenberg, J., Rentschler, J., Avner, P., & Hallegatte, S. (2019). Infrastructure disruptions: how instability breeds household vulnerability. Global Facility for Disaster Reduction and Recovery, World Bank, Washington DC.

[7] Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). Lifelines: The Resilient Infrastructure Opportunity. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/31805

[8] Obolensky, M., Erman, A., Rozenberg, J., Rentschler, J., Avner, P., & Hallegatte, S. (2019). Infrastructure disruptions: how instability breeds household vulnerability. Global Facility for Disaster Reduction and Recovery, World Bank, Washington DC.

[9] Braese, J., Rentschler, J., & Hallegatte, S. (forthcoming, 2019). Resilient infrastructure for thriving firms: A review of the evidence. Global Facility for Disaster Reduction and Recovery. World Bank, Washington DC.

[10] Koks, E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M.,Fraser, S., Hall, J., & Hallegatte, S. (forthcoming, 2019). A global multi-hazard risk analysis of road and railway infrastructure assets

[11] Limao, N., & Venables, A. J. (2001). Infrastructure, geographical disadvantage, transport costs, and trade. The World Bank Economic Review, 15(3), 451-479.

of US$151 billion a year.[12] And long-term impact may be significantly higher than short-term losses as firms experience the knock-on effects of foregone productivity.[13]

Conversely, there is evidence of significant returns associated with improved maintenance and resilience to climate change and natural disasters. Significant returns are associated with improved maintenance that precludes excessive repair costs associated with rebuilding significantly damaged infrastructure.[14] Moreover, economic benefits are expected for developing countries that invest in resilient infrastructure. Hallegatte, Rentschler, and Rozenberg estimate net benefits of US$4 for every US$1 invested in resilient infrastructure due to savings in repair costs as well as avoided social and economic damages.[15]

The Resilience Concept

The potential benefits of building more resilient infrastructure, particularly in disaster-vulnerable contexts, along with an acceptance of deep uncertainty associated with climate change, compels a resilience approach to infrastructure development. While disaster risk management (DRM) is a core component of infrastructure resilience, the concept for resilience additionally deals with process and resource features that can extend the capacity of a system to withstand and recover from shocks and stressors.

The Intergovernmental Panel on Climate Change defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions" (2012).[16] Moreover, infrastructure resilience has multiple levels with different types of benefits. The resilience of individual assets allows components of a system to withstand shocks, thus reducing overall costs. The resilience of networked infrastructure services refers to higher reliability at the system level. And the resilience of users captures the extent of negative impacts on people and economies as the result of a hazard.[17]

Resilient infrastructure assets are robust and designed to anticipate failures; resourceful to maintain or restore functionality following a shock; and built to be flexible, recoverable, and adaptable to change.[18] Robustness is gained via design and maintenance inputs to an asset that make it particularly durable or by building system redundancies. The robustness of an asset may be increased by engineering means, for example, by strengthening a structure identified as having high risk of exposure to a certain hazard. In the context of road transport infrastructure, this may be done via adaptation measures such as soil improvement, the addition of retaining walls, installation of more robust foundations and reinforcements, and improved drainage.[19]

---

[12] Rentschler, J., Kornejew, M., Hallegatte, S., Braese, J., & Obolensky, M. (draft, 2019). Underutilized potential: The business costs of unreliable infrastructure in developing countries. Global Facility for Disaster Reduction and Recovery, World Bank, Washington DC, and Bonn Graduate School of Economics, University of Bonn, Germany.

[13] Braese, J., Rentschler, J., & Hallegatte, S. (forthcoming, 2019). Resilient infrastructure for thriving firms: A review of the evidence. Global Facility for Disaster Reduction and Recovery. World Bank, Washington DC.

[14] Rioja, F. (2013). What is the value of Infrastructure Maintenance? A Survey. Infrastructure and Land Policies, 13, 347-365.

[15] Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). Lifelines: The Resilient Infrastructure Opportunity. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/31805

[16] IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/report/ar5/wg2/

[17] Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). Lifelines: The Resilient Infrastructure Opportunity. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/31805

[18] SuRe (2016). The Standard for Sustainable and Resilient Infrastructure v 0.3. Global Infrastructure Basel. 27 July 2016. http://www.gib-foundation.org/sure-standard/

[19] Miyamoto & World Bank (2019). Overview of engineering options for increasing infrastructure resilience: Final report. February 2019.

Resourcefulness requires identifying response strategies, prioritizing damage control actions, and mobilizing responses for recovery – i.e., designing processes and identifying and ensuring access to the resources that will be required in the case of a failure. In close relation, rapid recovery is supported by contingency planning, implementation of emergency response procedures, and plans to deploy resources and labor power to return operations to normal.

Resilience in Infrastructure Decision Making

Over the past few years, governments and their multilateral partners have increasingly recognized the importance of incorporating climate and disaster resilience considerations into infrastructure development plans and related construction and financing decisions. In order to more effectively prepare for uncertain geographical and hydrometeorological events, governments are being challenged to consider a wider set of options for increasing structural resistance and improving process-oriented resilience measures.

The potential medium- and long-term benefits of increased resilience must be considered alongside the short-term costs of resilient design and implementation. Proposed infrastructure projects must be compared and appraised in a manner that considers the costs and benefits of various options over the entire life-span of an asset, which often spans decades. The likely performance of infrastructure systems subject to natural hazards may be considered according to several parameters including damage probability, socioeconomic costs, business interruptions due to disrupted service, costs of repair, and other losses of functionality, all over the whole lifecycle of the asset or system.[20]

The need to consider multiple and whole-lifecycle factors in the face of climate and disaster uncertainty has led to rich discussions on *how* resilience may be incorporated into project design and selection. The challenge of organizing an expanded set of considerations into a functional and effective decision framework underpins the work documented in this report, which tests one approach to operationalizing resilience. This approach utilizes quantifiable resilience indicators that may be considered alongside other social, financial, economic, and environmental decision factors to inform project selection. That said, the expansive conceptual nature of resilience does not lend to the total quantification of all aspects of resilience. As such, the effort herein attempts to capture a few of the most significant vulnerabilities associated with potential natural disasters in order to at least partially bring resilience considerations into project design and selection processes.

The objective of this paper is to estimate the resiliency benefits for key socio-economic aspects under different road-upgradation scenarios and compare the results with regards to the related costs. The test case used is the East Road of the Malaita Road Network in the Solomon Islands, which has been selected primarily to pilot the methodology and examine its applicability. The parameters selected to measure resiliency were based on the key benefits the road provides to the people living around it – i.e. economic benefits proxied by travel time, access to hospitals and access to markets. In general, access to schools would also be a key parameter, but, in the case of Malaita, it was not considered a key functionality, as most primary students walk to school and most secondary students board at their schools during the week. Therefore, the road disruption causes very marginal interruption to this access. Since it was found that there were severe data constraints in Malaita, the report is based primarily on expert-inputs as well as geo-spatial data. It considers mainly technical improvements to road upgradation that might impact resiliency. However, it is acknowledged that other improvements on aspects such as maintenance contracts and availability of maintenance/repair funds can also positively benefit the ability of a road asset to recover faster post disruption.

---

[20] Ibid.

This report begins with a general overview of the Malaita Road Network, including the East Road and its overall locus within and impact on the geography, economy, and social experience of Malaita. The background also describes three proposed alternatives for road upgrading and a set of probable rainfall events likely to impact the road over its functional lifetime. Thereafter, the report details the mathematical approach to operationalizing the resilience concept in the context of the East Road and follows with the data and methodologies used to construct relevant resilience indicators for each of the three proposed upgrading options and baseline (status quo) scenarios. Following the documentation and analysis of results, the report concludes with a discussion of this case study's implications for more general efforts to structure resilience considerations in infrastructure decision-making as well as its limitations.

II. Background

The Solomon Islands is the Pacific's largest archipelagic nation, consisting of nearly 1,000 islands extending across 1,500 km from east to west. The country has enjoyed steady economic development over the past few decades, with annual average GDP growth of 2.8% annually between 2000 to 2009, and 4.7% annually between 2010 and 2016. GDP is expected to continue to grow by an average 2.9% each year over the period of 2019 to 2023 (IMF, 2018). Key drivers of economic progress have been growth in services, as well as development of the forestry and logging sectors.

Major threats to development, however, include the expected losses and damages associated with natural disasters and climate change. Solomon Islands is highly vulnerable to tropical cyclones, floods and droughts, landslides, volcanic eruptions, earthquakes, and tsunamis.[21] The country has been ranked among the 10 countries with the highest vulnerability and exposure to natural disaster risks.[22] In fact, seven major natural disasters over the past 30 years have caused significant losses of life and major economic damages. A 2014 flash flood in Guadalcanal, for example, displaced an approximate 10,000 people and caused damages and losses equivalent to 9% of the country's GDP. GFDRR estimates that natural hazards and climate change will cause average annual losses of US$20.5 million (3% of GDP) over the next half century.[23]

Moreover, road infrastructure remains a key area of development for the country and an important factor limiting trade and transport. The road network in Solomon Islands is publicly owned and operated. It is made up of approximately 1,500 km of roads: some 625 km (42%) are classified as main roads, 523 km (35%) are feeder roads, and 346 km (23%) as access roads. Three-quarters of the road network (including all the sealed roads) are in just three provinces: Guadalcanal (including the Capital Territory of Honiara), Malaita and Western Province. Only 184 km (29%) of the main road network (comprising 12% of the overall network) is sealed. Overall, 15% of the network is in fair to good condition, comprising 56% (104 km) of the sealed network and 11% (146 km) of the unsealed (gravel road) network.[24]

The country's road network extends 1,694 km across 30 islands. Most roads (66% of the network) are concentrated in only two provinces – Guadalcanal and Malaita. Only approximately 126 km (7.5% of the network) all located in Guadalcanal and Malaita are sealed with bitumen/asphalt, concrete, or tar, while the rest are unsealed coral, gravel, or dirt roads. Much of the road network is deteriorated due to natural disasters and conflict-related damage. Mountainous terrain presents an additional construction challenge.

---

[21] GFDRR, 2019. Building community resilience in the Solomon Islands: Helping communities manage disaster and climate risk. https://www.gfdrr.org/sites/default/files/publication/FINAL%20-%20Results%20in%20Resilience%20-%20Building%20Community%20Resilience%20in%20the%20Solomon%20Islands%20-%207.9.18.pdf

[22] World Risk Index, World Risk Report. 2016. http://collections.unu.edu/view/UNU:5763

[23] GDFRR, ibid.

[24] World Bank. 2019. Project Appraisal Document: Solomon Islands Roads and Aviation Project. http://documents.worldbank.org/curated/en/621001554084042298/pdf/Solomon-Islands-Roads-and-Aviation-Project.pdf

In its 2016-2035 National Development Strategy, the Government of the Solomon Islands recognized the need for improved infrastructure, particularly upgrading and better maintaining the road transport network.[25] While most of the country's roads are low-volume, they nevertheless provide key benefits to the citizenry by way of access to health care, education, employment, markets, and leisure, as well as by reducing the costs of transit and trade. For roads, specifically, the conventional choice of paving in Pacific Island States has been some version of flexible pavement, such as bituminous surface coating (BTC / "chip-seal") or asphalt. While these surface pavements generally perform well, they require routine maintenance, which is often lacking in Pacific Island countries. Concrete, on the other hand, while more costly with respect to initial construction, is also more robust and can yield lower whole-life costs due to reduced maintenance and repair.[26]

While much of the road network needs upgrading to improve surface quality (including paving a portion of the unsealed network), there is also a pressing need to increase the network's resistance to extreme weather and geological events and the effects of climate change. Improving road segments' capacities to withstand natural hazards such as rising sea level and flooding, for example, may require such measures as the use of concrete pavements for vulnerable sections of road. Concrete pavements have the potential to improve resilience over the lifetime of a road asset and may even prove cost effective due to increased ability to avoid catastrophic damage, but they have hardly been used in the Pacific Islands. Similarly, vulnerable unpaved sections that may be washed out during heavy rainfall may be made resistant to higher levels of impact with paving. But such measures come at an increased short-term construction cost. Within this context, this study aims to estimate resilience gains derived from a set of road-upgrading alternatives for a case study road – the East Road of Malaita – and the comparative costs of upgrading. This test case will both inform decision-making for the East Road and serve as an empirical test of efforts to incorporate resilience considerations in infrastructure project design and selection.

Malaita Road Network

Malaita is one of largest of the Solomon Islands, with an estimated population of 170,883 (according to 2012/13 HIES). The three primary roads of Malaita, namely the North Road (112.2 km), South Road (75.6 km) and East Road (41.7 km), together constitute nearly 60% of the road network on the island and carry the majority of vehicular traffic (Figure 1). These roads connect 19 of the 33 wards and provide access to 70% of the population.

Generally, however, conditions of the road network are poor, and many of the island's bridges are significantly deteriorated or structurally compromised.[27] Moreover, only 4% of the province's roads are sealed. While some of the sealed segments are short sections in Auki town, most are located along the North and South roads.[28] Only a reported 17.4 km of these main roads are sealed, and the remainder are unsealed coral gravel. Therefore, most of the road network is unsealed, poorly drained, and easily eroded.[29]

---

[25] Solomon Islands National Development Strategy, 2016-2035. https://www.adb.org/sites/default/files/linked-documents/cobp-sol-2017-2019-ld-01.pdf

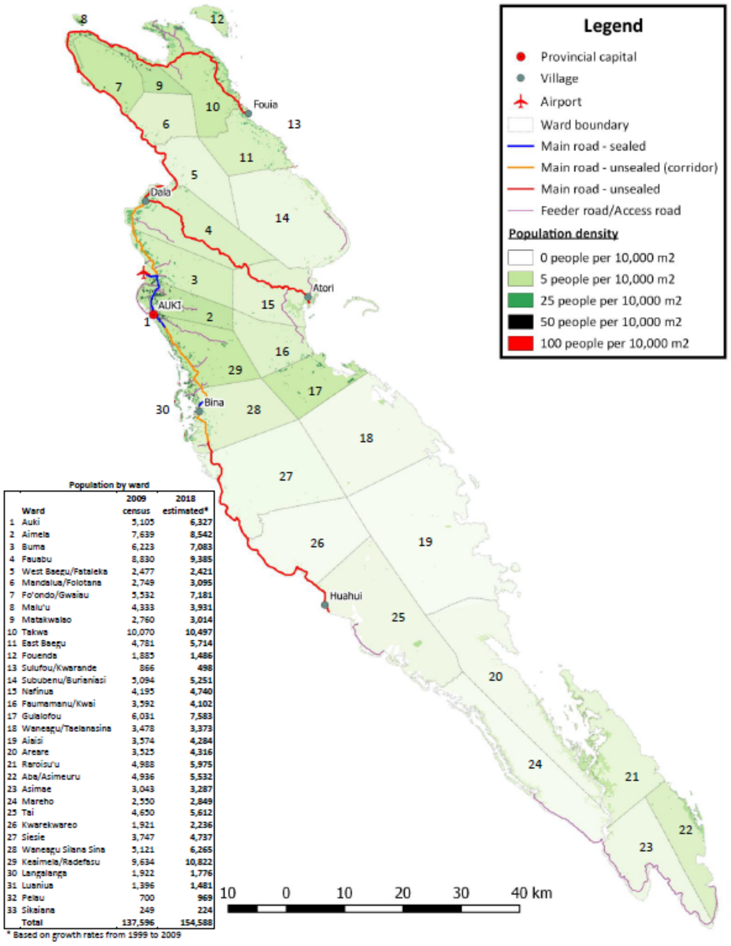
[26] Johnson, S. and Visser, A. (2018). Viability of concrete pavements for low-volume roads in Pacific Islands Countries. 21 August 2018. Unpublished report, World Bank.

[27] Only 23% of Malaita's bridges are concrete or steel bridges, compared with 40% in Western and Guadalcanal provinces and 62% for the Capital Territory of Honiara (World Bank, 2019).

[28] These include the first 7.6 km of the North Road, the first 1.5 km of the South Road and an additional 1.9 km section near Bina, and the 2.8 km road linking to the airport.

[29] Johnson, Sam William, Asif Faiz, and Alex Theo Visser. 2019. "Concrete Pavements for Climate Resilient Low-Volume Roads in Pacific Island Countries." The World Bank. http://documents.worldbank.org/curated/en/537681568381365403/Concrete-Pavements-for-Climate-Resilient-Low-Volume-Roads-in-Pacific-Island-Countries.

Figure 1. Malaita Road Network



Population by ward

	Ward	2009 census	2018 estimated*
1	Auki	5,105	6,327
2	Aimela	7,639	8,542
3	Buma	6,223	7,083
4	Fauabu	8,830	9,385
5	West Baegu/Fataleka	2,477	2,421
6	Mandalua/Folotana	2,749	3,095
7	Fo'ondo/Gwaiau	5,532	7,181
8	Malu'u	4,333	3,931
9	Matakwalao	2,760	3,014
10	Takwa	10,070	10,497
11	East Baegu	4,781	5,714
12	Fouenda	1,885	1,486
13	Sulufou/Kwarande	866	498
14	Sububenu/Burianiasi	5,094	5,251
15	Nafinua	4,195	4,740
16	Faumamanu/Kwai	3,592	4,102
17	Gulalofou	6,031	7,583
18	Waneagu/Taelanasina	3,478	3,373
19	Aiaisi	3,574	4,284
20	Areare	3,525	4,316
21	Raroisu'u	4,988	5,975
22	Aba/Asimeuru	4,936	5,532
23	Asimae	3,043	3,287
24	Mareho	2,550	2,849
25	Tai	4,650	5,612
26	Kwarekwareo	1,921	2,236
27	Siesie	3,747	4,737
28	Waneagu Silana Sina	5,121	6,265
29	Keaimela/Radefasu	9,634	10,822
30	Langalanga	1,922	1,776
31	Luaniua	1,396	1,481
32	Pelau	700	969
33	Sikaiana	249	224
	Total	137,596	154,588

* Based on growth rates from 1999 to 2009

Source: World Bank

Recent re-shaping and re-graveling works have improved unsealed sections, but due to high rainfall and steep topography, these roads are all subject to rapid deterioration and may be washed out during a single rainfall. While drainage structures are present in many areas, improvements are still required along several segments.[30] Insufficient maintenance to road surface and draining accelerates the tendency for rapid deterioration.

In response to the need to improve road quality and maintenance, the Malaita Road Improvement and Maintenance Program has been prepared, with its first phase financed as part of the World Bank-assisted Solomon Islands Roads and Aviation Project approved in March 2019. The project's initial assessment identified key needs as resealing and repairing currently sealed sections; improving the regime for grading and re-sheeting unsealed sections; sealing steep road segments and the high-traffic Dala–Auki–Bina corridor; and enhancing drainage and slope stabilization for segments most vulnerable to weather events.[31]

The East Road

Since upgrading needs are greatest and rain impacts most evident on the East Road, this study focuses on this particular part of the Malaita Road Network. The 42-kilometer, unpaved East Road traverses Malaita from the west at Dala, along the North Road, to the Atori port on the eastern coast. It runs through three wards with nearly 14,000 people and serves as the main access road for two other wards on the eastern coast, which are home to an additional 13,000 people.

Due to poor road conditions, traffic volumes are low (mainly small trucks and 4x4 vehicles, Figures 2 and 3) and transport costs high (approximately double what they are on the North and South roads). Moreover, the road has several steep gradients and crosses the island's mountainous center, accounting for an elevation differential of 400 meters. Steep sections account for 20 km in the center of the road and include

---

[30] Cross drainage structures and lateral drains are present in many places. There are 368 recorded pipe culverts and 27 box culverts along the three main roads.

[31] World Bank, 2019. Project Appraisal Document, Solomon Islands Roads and Aviation Project. March 7, 2019. http://documents.worldbank.org/curated/en/621001554084042298/pdf/Solomon-Islands-Roads-and-Aviation-Project.pdf

several long, steep sections of several kilometers each. These are particularly vulnerable to erosion (Figure 4).

Figure 2. Passenger truck on East Road

Figure 3. 4x4 vehicle on East Road

Moreover, because of steep gradation and poor maintenance, rain runoff rapidly erodes the coral gravel road and regularly reverses re-graveling improvements.[32] The poor resulting conditions impede public transport. Since many cars cannot handle the eroded surface, residents must rely on transport via open trucks. Traveling times are extended, and passenger safety is a key concern. As such, road sealing with bitumen or concrete pavement, particularly for the most vulnerable road sections, has become a policy priority, and much of the road requires improved drainage.

Figure 4. Typical erosion damage of long slope on East Road

Naturally, sealing parts of the East Road and improving drainage and maintenance practices are likely to increase short-term costs beyond the average status quo. Decision makers must make informed decisions about the investment levels and alternative options to upgrade segments of the road. These options may be differentiated by the segments selected for upgrading and the standards of structural resistance adopted for each segment. Comparing the long-term, whole-lifecycle costs[33] and benefits of various options – including resiliency gains – will help decision makers to identify the most effective and efficient options. The options proposed for comparison are explained in section IV. First, however, the underpinning theoretical construction of resilience indicators is explored in the following section.

---

[32] World Bank, 2019. Ibid.

[33] In this paper, lifecycle costs only constitute the road agency (authority) costs that are comprised of expenses for planning, construction, design, maintenance, and rehabilitation. User costs (e.g. delay costs, accident costs and vehicle operation costs) are not included.

Operationalizing the resilience concept for use in practical analysis requires defining resilience in a measurable way. The resilience concept captures many interrelated aspects of resistance and recoverability, not all of which can be practically measured or independently considered without creating a significant burden on analysts and decision makers alike. Therefore, the construction of resilience indicators requires identifying a few key aspects on which to focus.

Operationalizing the Resilience Concept

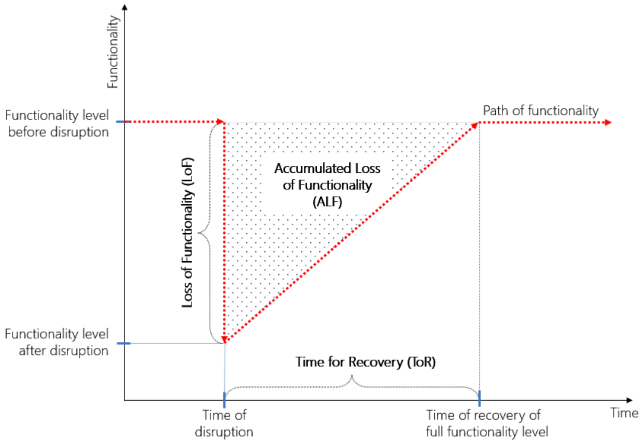
Previous work by Marcelo et al (2018) developed a methodology for constructing resilience indicators based on a notion of resilience defined as (a) an asset's ability to withstand shocks in such a way that minimizes functionality losses (robustness or resistance), and (b) an asset's capacity to recover functionality following a disaster event (recoverability). The identified 'functionalities' are intended to capture the most important or critical social, environmental, and economic benefits associated with an infrastructure asset. If such proposed functionalities can be specifically defined and measured, expected functionality *losses* may be modeled under various disaster or climate change impact scenarios.

Measures of **Loss of Functionality (LoF)** may reflect economic losses in monetized terms, based, for example on lost access to markets or higher transportation costs. Alternatively (or in addition), LoF measures may capture losses of life due to interrupted access to provisions or medical care, losses of travel time in average hour terms, or any number of other functionalities deemed of interest to policy makers and citizens.

With respect to recoverability as a key aspect of resilience, it refers to the amount of time required to restore service under various impact scenarios and, thus, the key functionalities identified. The **Time for Recovery (TfR)** may be set as the time for full recovery to pre-event services levels (functionality levels), or some stipulated level of basic service. The TfR will depend on the systems and processes in place, availability of resources, and physical and geographical attributes of the asset at hand.

The extent of losses due to an impact depends on both the magnitude of functionality lost as well as the duration of the recovery period. When the Loss of Functionality is considered over the Time for Recovery, an Accumulated Loss of Functionality (ALF) can be calculated for each identified functionality. Mathematically, ALF is equal to the integral of the LoF function over the interval between the disruption and the end of the TfR period. Figure 5 illustrates the process of recovery of asset functionality following a disruption. ALF is equal to the shaded area in Figure 5.

Figure 5. Concept of Resilience and Functionality



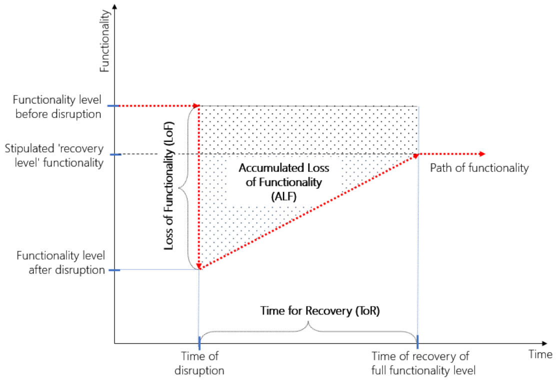
Source: Authors' composition

Note: Path of recovery may be linear or non-linear, depending on the context and functionality being observed.

Selecting Loss of Functionality (LoF) Indicators for the East Road Case

Naturally, the selection of resilience indicators will depend on context, as the most important aspects of resilience will differ from project to project and region to region, particularly considering the many different possible combinations of geography, hazard exposure and vulnerability, type of infrastructure service, and characteristics of the population served.

Figure 6. Concept of Resilience and Functionality, Recovery to Lower Level



Source: Authors' composition

The definition and mathematical calculation of ALF may differ if the level deemed to be a recovery service level is set lower than the pre-event level of service. In Figure 6, for example, recovery is set to a lower level than full pre-event functionality. This may capture a point, for example, where emergency services may gain access to a road or when roads have been opened but are not yet fully repaired to a level that facilitates pre-event travel time or traffic volume.

In the context of the Malaita East Road, key functionality indicators were identified based on inputs from sector and local transport policy experts. These experts helped identify the most appropriate assumptions and approaches to estimate the baseline road functionalities as well as the expected functionality losses under various hazard event scenarios.

Three key functionalities of the East Road were identified: economic loss proxied by travel time, access to hospitals, and access to markets. These functionalities and their definitions are detailed in the following section, but all are based on a conception of ALF that considers functionality losses due to roads being made impassable after exposure to heavy rain.

Travel Time

In terms of functionality loss for road infrastructure, the simplest way to assess the economic impact resulting from a disaster event is by measuring its effect on travel time between a representative origin-destination pair (i.e. between Dala and Atori in this case). According to standard transport economics theory, the consumer surplus is a key consideration when assessing the economic benefit of a road network (de Palma, Andre, et al, 2011, World Bank, 2005), which reflects the time *saved* from a hypothetically longer travel duration that a consumer-traveler may use for other activities. This naturally must also be linked to the traffic volumes to estimate the total time saved across all users. Currently on the East Road, only 4-wheel drive vehicles are able to use it because of the steep gradients and gravel surface. With improved roads, travel time would be reduced, and vehicle volumes increased.

In order to calculate the consumer surplus, a traffic demand function needs to be specified. Traffic demand depends on the generalized cost of transportation, which includes costs to the user such as travel time, safety, vehicle ownership and operation, and taxes, tolls, and other fares (Lee, 2000; Litman, 2017). If the generalized cost of transportation is proportional to travel time, holding other costs constant, transportation volume may be expressed as a function of travel time and vice versa.

Access to Markets

Access to markets allows the population living along the East Road to participate in trade. The island's primary market is located in Auki, where most farmers sell their crop yields. Auki lies to the south of the western terminus of the East Road (along the South Road); thus, any disruption to an East Road segment would interrupt access to the market for anyone located to the east of the disruption. Smaller harvests are often sold locally in Dala, a secondary market, but the main source of income comes from activities in Auki.

Access to these markets is measured by the number of people with access to the key markets at Auki within a 3-km buffer on the East Road. Conversely, loss of functionality associated with access to markets refers to the people who would not be able to access Auki if a heavy rain makes segments of the road impassable.

Access to the Hospital

Auki is also home to the island's only hospital. As with the main market, any disruption to an East Road segment would interrupt access to the hospital in Auki for people east of the disruption. Given that there are no alternatives on the island, a buffer of 10 km was selected as the delineation of an access zone, based on expert advice. This buffer recognizes that even residents living a distance from the East Road need to access the road for emergency care in Auki.

Time for Recovery

While full recovery time depends on the extent and location of damages, assumptions about Time for Recovery (TfR) were based on expert opinion and past experiences in similar contexts. These consultations suggested that typically, it would take about two days to mobilize contractors and resources and subsequently, on average, roads could be made passable using gravel at 100 meters per day.

To make the results between scenarios comparable, the TfR included in the estimations is up to the recovery level of the status quo as services would begin to flow at that point. However, to recover completely to pre-disruption level for Medium Design (MD), High Design (HD) and Sealed Long, Steep Sections (SLS) scenarios would take a significantly longer time given the materials required.

III. Estimating Resilience Indicators for the East Road

The East Road requires upgrading both to improve road conditions under normal conditions as well as to increase the resilience of communities in Malaita to hydrometeorological hazards – namely, flooding and heavy rain. The resistance of the roads to rainwater run-off and the effects of flooding depends on constructing more robust surfaces and improving drainage systems. Because these improvements come at a cost, decisions must be made about how to best balance the costs and benefits of resilience-enhancing measures to avoid overbuilding roads and wasting precious resources.

The following section describes the analytical approach used to calculate quantifiable indicators of the resilience aspects identified as most important for the East Road case, employing the concepts described above. These, in turn, may inform the comparison of costs and benefits of resilience measures for the East Road case. The analytical approach, when presented in detail, also demonstrates how complex operationalizing even simply-defined aspects of the resilience is in practice.

The steps to estimate functionality losses, costs of repair, and times for recovery described above include:

(a) Specifying alternative road options (scenarios);
(b) Specifying weather events to be modeled, including intensity and probable frequency;
(c) Identifying road segments likely to be damaged by each rain event, for each project scenario;
(d) Estimating the number of people affected by road segment damages or closures over the lifespan of the road, for each scenario
(e) Estimating time required to attain a recovery service level (TfR) for each rain event, for each project scenario.

The analysis assumed a *whole-lifecycle approach* to compare the relative resilience of the four alternatives. The accumulated functionality losses (associated with a single event) for each combination were aggregated over the lifespan of the road – in this case, 30 years – during which time multiple heavy rains would be expected to affect the road.

Note that the exact frequencies of these rain events are unknown; however, the probability of a specific type of rain event occurring at least *'n'* times during the 30-year lifecycle of the road can be estimated and used in the calculations of costs and ALF. For example, the probability of an "extreme intensity" 10-year rainfall occurring at least four times during the lifecycle of the road is 35%. With this information, a risk averse decision maker may decide to include, in the cost estimations, the recovery expenses associated with at least four of these extreme events. For a less cautious decision maker, conversely, this risk level may not be high enough to consider additional recovery expenses in the cost estimations. In other words, the costs and expected losses associated with future rain events depend on the selected probability threshold which, in turn, represents the risk aversion level of the decision maker.

The losses associated with each predicted hazard yield *sums* of the number of people affected by disruptions. The hypothetical unit is akin to accumulated 'person-disruptions' over the lifespan of the asset, which may count multiple disruptions that affect some of the same people.

A. Road Upgradation Options

Road upgradation can be undertaken up to varying degrees, using diverse materials that have both cost as well as climate resilience implications. The scenarios listed below identify the structural characteristics of the road under each upgradation option, specified at a road segment level, vis-à-vis the base scenario which consists of the road remaining entirely in gravel but with regular maintenance.

Scenario 0 represents the **Status Quo (SQ)**, wherein no upgrading is undertaken and the practice of grading and re-graveling as needed (typically every 1-3 years) to repair damaged road segments is continued. Additionally, three upgraded scenarios are considered.

Scenario 1 represents a **Medium Design (MD)**, wherein road sections with gradients between 9-15% are resurfaced with a bituminous surface coating (BTC /'chip-seal') and sections with gradients of 15% or higher are concrete cement-paved. Sections with gradients of less than 9% are left graveled. Scenario 1 also constructs lined drains for all segments with 9% gradients or above (all sealed sections).

Scenario 2 represents a **High Design (HD)** that improves upon the medium design by extending chip seal resurfacing to any sections with gradients exceeding 6% up to 15% and also concrete cement-paving segments with gradients exceeding 15%. Scenario 2 constructs lined drains for all segments with 6% gradients or above (all sealed sections).

Lastly, **Scenario 3** takes a different approach by sealing roads only if they are both long and steep. This **Sealed Long, Steep Sections (SLS)** design aims to upgrade only those slopes most susceptible to run-off damages due to extended lengths coupled with gradients of 6% or above. Where there are long, sloped road segments, water often flows along the road and accumulates, causing drainage problems and quick deterioration of graveled surfaces. These represent some of the most problematic sections of the East Road and would be targeted under this scenario for priority sealing. Road segments that are steep but short (less than 250 m) would be left graveled.

For all improved scenarios, concrete cement is proposed for any upgrading over 15%, since chip-seal does not typically work well on high gradients.

Using Global Positioning System (GPS) tracking records for the Malaita East Road from Atori to Dala, 5,856 road segments with gradient details were delineated and mapped using geographic information system (GIS) mapping software. These segments were mapped for the current road and also used to model surface conditions defined by the proposed upgrading projects.

Figures 7-9 show the results of mapping the various alternatives. The maps are color-coded by the gradient range of each segment. Therefore, they reflect the proposed surface types associated with each scenario. Green segments represent unsealed gravel road, yellow segments represent chip-sealed (BTC) road, and red segments represent concrete-paved road segments.

In the current state, Scenario 0, road segments are unsealed gravel. Figure 7 shows the 'medium design', Scenario 1. In this map, green represents sections with gradients below 9%, which would be left unpaved; yellow for gradients between 9 and 15%, which would be sealed with BTC; and red for gradients above 15%, which would be concrete cement-paved.

Figure 8 shows Scenario 2, the 'high design'. In this map, green represents segments with gradients below 6%, which would remain gravel; yellow for segments with gradients between 6% to 15%, which would be sealed with BTC; and red for segments with gradient above 15%, which would be concrete cement-paved.

Lastly, Figure 9 represents Scenario 3, the 'sealed long, steep sections' (SLS) design, wherein long, steep sections of the East Road are sealed with BTC. This alternative aims to seal long segments with extended slopes of 6% or above. In the map, green represents road segments that are either flat or have an extended slope of 250 meters or less (normal and low risk of disruption); yellow for segments with an extended slope of 250-500 meters (challenging with potential for disruption); and red for segments with extended slopes of more than 500 meters (highly problematic with high potential for disruption). Based on this classification scheme, there are 27 sections with extended slopes of 250-500 meters (average segment length 165 meters and a total of 4.5 kms) that are considered challenging, and 14 sections with extended slopes of more than 500 meters (average segment length 840 meters and total length of 11.7 km).

Figure 7. Scenario 1 'Medium Design' scenario gradient map

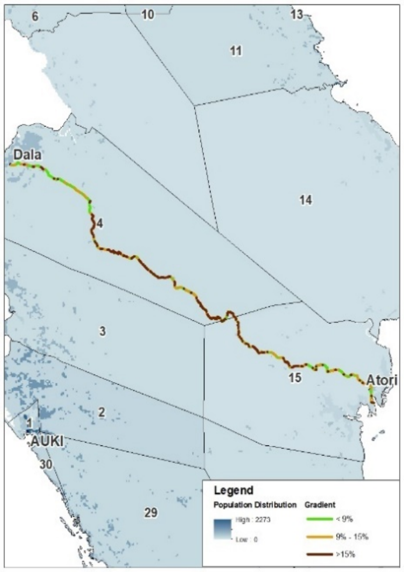
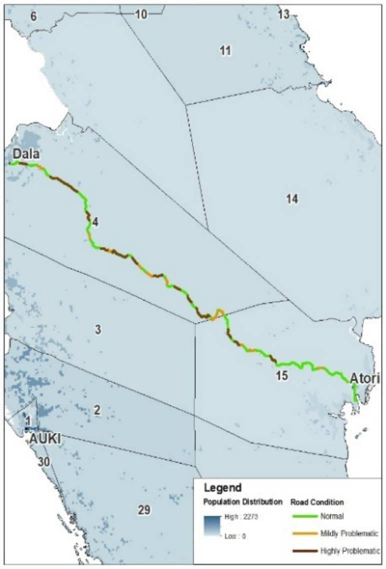


Figure 8. Scenario 2 'High Design' scenario gradient map

Figure 9. Scenario 3 'Sealed Steep Sections Design' scenario gradient map



Source: Authors' renderings

Table 1 summarizes the road upgradation options along with length under each type of surface type.

Table 1. East Road construction alternatives

	Scenario	Details	
		Combined Segment Length (km)	Specifications
0	Status Quo (SQ) (no upgrading)	41.533	Gravel surface with earth drains for all segments
1	Medium Design (MD)	29.546 7.335 4.652	Gravel surface with earth drains for segments with <9% grade Bituminous sealed surface with lined drains for segments from 9-15% grade Cement concrete surface with lined drains for segments with >15% grade
2	High Design (HD)	22.355 14.526 4.652	Gravel surface with earth drains for segments with <6% grade Bituminous sealed surface with lined drains for segments from 6-15% grade Cement concrete surface with lined drains with >15% grade
3	Sealed Long, Steep Sections (SLS)	25.34 16.193	Gravel surface with earth drains for shorter or lower-gradient segments Bituminous sealed surface with lined drains for long, steep sections where road segments with gradients of 6% or above extend for 250 meters or more

B. Climate Events Likely in Malaita

Rainfall data specifically for Malaita are not currently available but, based on expert input, a set of probable hazard events was selected as a basis for modeling the expected effects on the current road and each of the proposed upgraded road alternatives over the 30-year lifespan of the road. These events include the following three heavy rainfall hazards with varying intensities.

- A high intensity rainfall with a return period[34] of 3 years;
- An extreme intensity rainfall with a return period of 10 years; and
- A catastrophic rainfall with a return period of 30 years.

While these hazards certainly do not capture all the natural risks to which the road would be subject, they represent events that typically render roads unpassable in Malaita.

Note that it would be wrong to assume that a 3-year rain event will occur only once in 3 years. In fact, any of the rainfall events listed above could happen in a single year. The annual probability of occurrence (often referred to as the Annual Exceedance Probability) is simply the inverse of the return period. For example, a rain event with an associated return period of 1 in 3 years has a probability of occurrence, in any given year, of 1/3 or 0.33 (or 33%).[35]

The probability (P) of getting (M) rainfall events within a specific (N) years period is described using the binomial probability mass function as it follows a binomial distribution as shown below

$$\text{Probability (M successes from N trials)} = \binom{N}{M} P^{M}(1-P)^{N-M}$$

Table 2 summarizes the calculations for the three type of rain-events over a 30-year time period. Based on these results, if the decision maker adopts a probability threshold of 50%, the number of rain-events likely in the 30-year period would be 10 for 3-year rain-events, 3 for 10-year events and 1 for 30-year events. Alternatively, should a more conservative probability of 30% be utilized, the number of events would be 12, 5 and 2 for the 3-, 10- and 30-year events, respectively. For an illustration purpose, this paper uses a probability threshold of 50%.

---

[34] A return period is an estimate of how long it will be between rainfall events of a given magnitude.

[35] Probability is expressed in mathematical terms and can assume a value of 0, 1 or any value in between. A probability of zero (p=0) indicates that an event has no chance of occurring while a probability of one (p=1) indicates that an event is certain to occur.

Table 2: Probability of the rainfall event occurring a specific number of times in the 30-year lifespan of the road

Probability of Occurrence		0.33	0.10	0.03
Recurrence Interval (years)		3	10	30
No. of occurrences	1	0.00	14.13	37.21
	2	0.06	22.77	16.69
	3	0.29	23.61	4.82
	4	0.98	17.71	1.01
	5	2.50	10.23	0.16
	6	5.14	4.74	0.02
	7	8.67	1.80	0.00
	8	12.28	0.58	
	9	14.78	0.16	
	10	15.29	0.04	
	11	13.69	0.00	
	12	10.68		
	13	7.28		
	14	4.36		
	15	2.29		
	16	1.06		
	17	0.429		
	18	0.152		
	19	0.047		
	20	0.013		
At least once in 30 years		1.00	0.96	0.64

The potential damage to the East Road would be different under the different rainfall events since it depends on the type of paving (gravel, bituminous surface treatment, or concrete) and drainage options (gravel or lined) associated with defined gradient ranges. Using expert input, the effects of each rain event on various combinations of surface type and road gradient were identified and are detailed in Table 3.

Table 3. Rain event effects by surface type and gradient

	3-year rain event						10-year rain event								30-year rain event									
	Gravel			Chip seal		Concrete	Gravel				Chip seal			Concrete	Gravel				Chip seal				Concrete	
Gradient	<9%	9-15%	>15%	<15%	>15%	All	<6%	6-9%	9-15%	>15%	<9%	9%-15%	>15%	All	<6%	6-9%	9-15%	>15%	<6%	6-9%	9-15%	>15%	<15%	>15%
Effect	Not affected	10% of length disrupted	20% of length disrupted	Not affected	5% of length disrupted	Not affected	Not affected	5% of length disrupted	15% of length disrupted	30% of length disrupted	Not affected	5% of length disrupted	10% of length disrupted	Not affected	2.5% of length disrupted	10% of length disrupted	20% of length disrupted	40% of length disrupted	2.50%	10%	20%	40%	Not affected	10% of length disrupted

These assumptions drive the estimation of damage to the roads as well the impact on the different functionality levels and the time it takes to recover to status quo road service levels.

C. Predicting Road Disruptions

By combining the information on the likely impacts of hazard events on road segments of a particular surface type and gradient level, the accumulated disruption of the East Road over 30 years was estimated for each road scenario. These disruptions are detailed in Table 4.

Table 4. Rain event disruptions by scenario

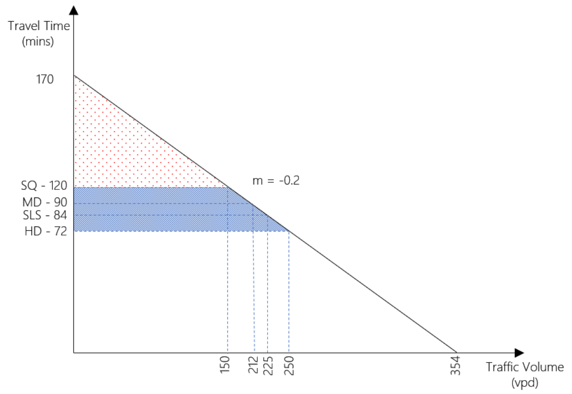
Scenario 0. Status Quo (SQ)							
Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years (km)	Total disruption 30 years (km)
GR	<6%	22.4	2.5%	0.6	30	0.6	0.6
GR	6%-9%	7.2	5%	0.4	10	1.1	1.8
GR	6%-9%	7.2	10%	0.7	30	0.7	
GR	9%-15%	7.3	10%	0.7	3	7.3	12.1
GR	9%-15%	7.3	15%	1.1	10	3.3	
GR	9%-15%	7.3	20%	1.5	30	1.5	
GR	>15%	4.7	20%	0.9	3	9.3	15.4
GR	>15%	4.7	30%	1.4	10	4.2	
GR	>15%	4.7	40%	1.9	30	1.9	
Total		41.5				29.8	29.8
Scenario 1. Medium Design (MD)							
Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years	Total disruption, 30 years
GR	<6%	22.4	2.5%	0.6	30	0.6	0.6
GR	6%-9%	7.2	5%	0.4	10	1.1	1.8
GR	6%-9%	7.2	10%	0.7	30	0.7	
BT	9%-15%	7.3	5%	0.4	10	1.2	1.9
BT	9%-15%	7.3	10%	0.7	30	0.7	
CC	>15%	4.7	10%	0.5	30	0.5	0.5
Total		41.5				4.8	4.8
Scenario 2. High Design (HD)							
Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years	Total disruption, 30 years
GR	<6%	22.4	2.5%	0.6	30	0.6	0.6
BT	6%-9%	7.2	2.5%	0.2	30	0.2	0.2
BT	9%-15%	7.3	5%	0.4	10	1.2	1.9
BT	9%-15%	7.3	10%	0.7	30	0.7	
CC	>15%	4.7	10%	0.5	30	0.5	0.5
Total		41.5				3.1	3.1
Scenario 3. Steep, Long Slopes Design (SLS)							
Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years	Total disruption, 30 years
GR	<6%	17.1	2.5%	0.4	30	0.4	0.4
BT	<6%	5.3	N/A	N/A	N/A	N/A	
GR	6%-9%	3.5	3%	0.1	10	0.3	0.5
GR	6%-9%	3.5	5%	0.2	30	0.2	
BT	6%-9%	3.7	2.5%	0.1	30	0.1	
GR	9%-15%	3.0	5%	0.2	3	1.5	3.6
GR	9%-15%	3.0	7.5%	0.2	10	0.7	
GR	9%-15%	3.0	10%	0.3	30	0.3	
BT	9%-15%	4.3	5%	0.2	10	0.6	
BT	9%-15%	4.3	10%	0.4	30	0.4	
GR	>15%	1.8	10%	0.2	3	1.8	5.1
GR	>15%	1.8	15%	0.3	10	0.8	
GR	>15%	1.8	20%	0.4	30	0.4	
BT	>15%	2.9	2.5%	0.1	3	0.7	
BT	>15%	2.9	10%	0.3	10	0.9	
BT	>15%	2.9	20%	0.6	30	0.6	
Total		41.5				9.6	9.6

D. Estimating Functionalities

Using the information mentioned above, the ALF associated with each of the functionalities over a 30-year period is calculated. This sub-section details the calculation process for each of the three functionalities.

1. Economic Loss Associated with Travel Time and Travel Volume

Figure 10. Traffic Demand Function



The current travel time along the extent of the East Road is approximately two hours with a vehicle volume of 150 vehicles per day (as per the survey conducted by the World Bank team). Sealing works under the high-design scenario could improve travel time by up to one hour as allowable road speed would increase to 40 km per hour, given the steep inclines. Concurrently, this would also affect travel volumes as more than just trucks and 4x4 vehicles would be able to use the road. Therefore, within the context of it being in general a low-volume road, it is assumed that traffic volume would increase to a maximum of 250 vehicles per day.

Using this information, we derive the slope of the traffic demand function and estimate the traffic volume given the expected travel time for the other scenarios (Figure 10). This allows us to estimate the 'consumer surplus' in terms of the time saved on the road and increased usage due to the better quality resulting from the upgradation. For example, for status quo (SQ) scenario, the consumer surplus would equal to (150*50)/2=3,750 (dotted area in Figure 10) whereas the same for high design (HD) scenario would be (250*98)/2=12,250 (dotted + checked area in Figure 10).

Therefore, the functionality levels (pre-disruption) for each road upgradation scenario would be equal to its consumer surplus as detailed in Table 5 below:

Table 5: Pre-Disruption Functionality Level

Design Scenario	Consumer Surplus/ Functionality Level
SQ	3,750
MD	8,500
HD	12,250
SLS	9,675

Post disruption, while for 2 days before repair work begins, there will no traffic flow between Dala and Atori, as repair work begins, segments will open leading to increasing traffic flow and will be estimated up to the functionality level of SQ at which point the entire road is passable, though not up to pre-disruption levels for upgraded scenarios.

2. Access to Markets and the Hospital

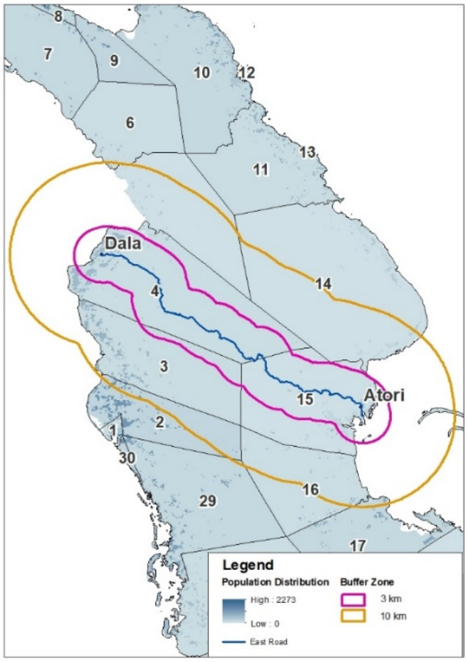
To estimate the loss of functionality in relation to the access people have to markets and hospitals, it was required to estimate two aspects : 1) the current number of people with access to these services when there is no disruption and 2) the average number of people affected due to disruption caused by the different rainfall events under each road upgradation scenario. In order to investigate this, geo-spatial analysis was undertaken along with running multi-simulations (100 run) to test the impact of different segments breaking down under each rainfall type-road upgradation scenario. The steps followed are detailed below:

2.1 Establishing an Access Baseline

Before these linkages could be considered, a baseline of access was established. This was done by imposing two hypothesized physical buffer zones along the East Road. A 3-km buffer zone was used to define the space enclosing people with reasonable access to the market, and a 10-km buffer zone was used to define the space enclosing people with reasonable access to the hospital. These buffer zones were used to calculate the populations with baseline road access for the two 'access' functionalities (hospital and markets), under normal circumstances (i.e., no disruption), within the two primary wards along the East Road – Faubu (#4) and Nafinua (#15). Figure 11 shows the mapping of the two buffer zones.

Figure 11. Buffer zones for East Road population estimations

Buffer Zone	WorldPop Estimates (2015)
3-km buffer 🟪	10,648
10-km buffer 🟨	31,867



Source: Authors' composition

The baseline populations served by the East Road (within the buffer zones) were established by utilizing WorldPop open source data. To estimate the number of people affected by rain event, however, a series of models were run to simulate the locus of impacts for each rain event (3-, 10-, and 30-year events) and their subsequent effects on access. Repeated events might affect the same people, and so, the cumulative impacts over the lifetime of the road can be thought of as 'person-disruptions' – i.e., the sum of individual disruptions. If, for example, an individual living on the East Road was cut off from access to hospitals three times over the thirty-year period, this experience would account for three person-disruptions.

2.2 Linking Hazards to Road Disruptions

While the locations of disruptions are not predictable, the percentage of overall road length affected by one of the three significant rain events is as detailed in Tables 3 and 4. Estimations can be made regarding the overall length of damaged roads expected for each event and project alternative, as shown in Table 6.

Table 6. Average cumulative damages due to rain events, by road alternative

Rain Event Frequency	Design Scenario		Gradient Profile	% Affected Length	Cumulative Segment Length (km)	Affected Length (km)	Total Affected Length (km)
3-year Rain (10 times)	SQ		9-15%	10%	7.33	0.733	1.653
			>15%	20%	4.6	0.92	
	MD		-	-	-	-	0
	HD		-	-	-	-	0
	SLS	Gravel	9-15%	5%	3	0.15	0.399
			>15%	10%	1.77	0.177	
		Chip Seal	>15%	2.5%	2.87	0.072	
10-year Rain (3 times)	SQ		6-9%	5%	7.19	0.36	2.84
			9-15%	15%	7.33	1.10	
			>15%	30%	4.6	1.38	
	MD		6-9%	5%	7.19	0.36	0.727
			9-15%	5%	7.33	0.367	
	HD		9-15%	5%	7.33	0.367	0.367
	SLS	Gravel	6-9%	3%	3.49	0.105	1.099
			9-15%	7.5%	3	0.225	
			>15%	15%	1.77	0.266	
		Chip Seal	9-15%	5%	4.33	0.217	
			>15%	10%	2.87	0.287	
30-year Rain (1 time)	SQ		<6%	2.5%	22.36	0.558	4.584
			6-9%	10%	7.19	0.719	
			9-15%	20%	7.33	1.466	
			>15%	40%	4.6	1.84	
	MD		<6%	2.5%	22.36	0.558	2.471
			6-9%	10%	7.19	0.719	
			9-15%	10%	7.33	0.733	
			>15%	10%	4.6	0.46	
	HD		<6%	2.5%	22.36	0.558	1.932
			6-9%	2.5%	7.19	0.180	
			9-15%	10%	7.33	0.733	
			>15%	10%	4.6	0.46	
	SLS	Gravel	<6%	2.5%	17.06	0.427	2.950
			6-9%	5%	3.49	0.175	
			9-15%	10%	3	0.3	
			>15%	20%	1.77	0.354	
		Chip Seal	6-9%	2.5%	3.7	0.093	
			9-15%	10%	4.33	0.433	
			>15%	20%	2.87	0.574	

2.3 Linking Road Disruptions to Access

While the available information allows us to estimate the share of the road in a particular gradient that is likely to fail during a specific rainfall event, the exact locations of the disruptions remain unknown. Given that there are nearly 6,000 segments in the road, 100 random simulations were conducted to test the impact of various road segment closures (based on specific gradient levels) on the overall access to the road’s western-most point.

Simulations were run wherein different road segments along the East Road would be hypothetically impacted by the 3-, 10-, and 30-year rain events according to the overall lengths described in Table 6 above. To do so, an automated bootstrapping method was used to calculate 100 possible outcomes for segment-level impact (i.e., which set of segments might be disrupted) across the entire East Road. This methodology is described further in Annex 2.

For each run of the simulation, the west-most disrupted road segment was identified. With each simulation, the population within the buffer zones to the *east* of this point was counted as the population cut off from access to the main market or hospital at Auki, respectively. From this number, the number of people living within a 3-km distance of the disrupted segment for markets and 10-km distance for hospitals were excluded, since we assume that they can just walk across (as depicted in Figure 12). The final estimated populations affected by a given rain event and road upgrading alternative are averages of the model-run outcomes for this type of exercise. The per-event affected populations for the 3-km are detailed in Table 7 and for the 10-km in Table 8.

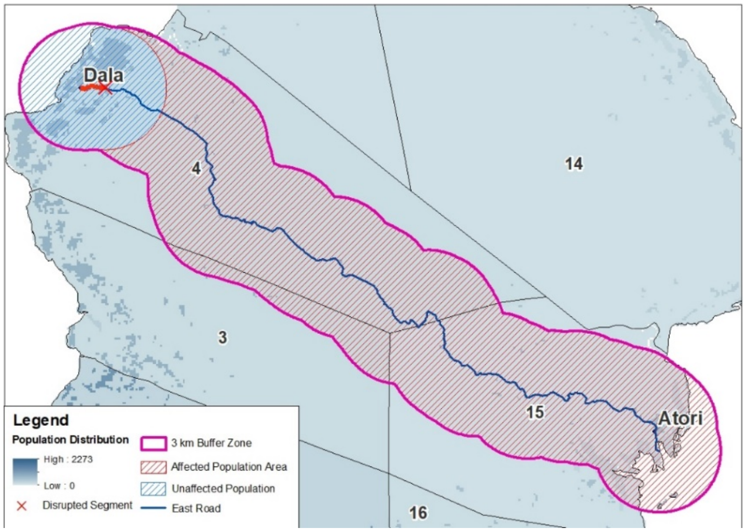
Table 7. Affected population in 3-km buffer zone, per single rain event

Rain Event Frequency	Design Scenario	Total Affected Length (km)	Affected Population (Max)	Affected Population (Min)	Affected Population (Average)
3-year Rain (10 times)	SQ	1.653	8,635	7,991	8,428
	MD	0	0	0	0
	HD	0	0	0	0
	SLS	0.399	8,635	6,448	7,890
10-year Rain (3 times)	SQ	2.84	8,635	8,336	8,532
	MD	0.727	8,635	7,992	8,449
	HD	0.367	8,635	6,220	8,219
	SLS	1.099	8,635	7,953	8,403
30-year Rain (1 time)	SQ	4.584	8,638	8,378	8,588
	MD	2.471	8,638	8,336	8,577
	HD	1.932	8,638	8,336	8,554
	SLS	2.950	8,638	8,259	8,562

Table 8. Affected population in 10-km buffer zone, per single rain event

Rain Event Frequency	Design Scenario	Total Affected Length (km)	Affected Population (Max)	Affected Population (Min)	Affected Population (Average)
3-year Rain (10 times)	SQ	1.653	22,947	21,283	22,400
	MD	0	0	0	0
	HD	0	0	0	0
	SLS	0.399	22,947	16,387	20,900
10-year Rain (3 times)	SQ	2.84	22,947	22,170	22,671
	MD	0.727	22,947	21,286	22,458
	HD	0.367	22,947	15,518	21,826
	SLS	1.099	22,947	21,169	22,343
30-year Rain (1 time)	SQ	4.584	22,949	22,268	22,822
	MD	2.471	22,949	22,170	22,791
	HD	1.932	22,949	22,170	22,730
	SLS	2.950	22,949	22,025	22,754

Figure 12. Example of Affected population area under 3 years rain event



The average figures (as detailed in Tables 9 and 10) were selected in order to estimate the number of people affected under each scenario combination which would define the functionality level (i.e. number of people with access to the market and hospitals) post-disruption.

Table 9. Affected population in 3-km buffer zone

Scenario	Affected Population by Single Event		
	3-year Rain	*10-year Rain*	*30-year Rain*
SQ	8,428	8,532	8,588
MD	0	8,449	8,577
HD	0	8,219	8,554
SLS	7,890	8,403	8,562

Table 10. Affected population in 10-km buffer zone

Scenario	Affected Population by Single Event		
	3-year Rain	*10-year Rain*	*30-year Rain*
SQ	22,400	22,671	22,822
MD	0	22,458	22,791
HD	0	21,826	22,730
SLS	20,900	22,343	22,754

E. Estimating Time for Recovery

While recovery time may vary depending on the extent of road damage, assumptions about Time for Recovery (TfR) were based on expert opinion and past experiences with road repairs in similar contexts. These consultations suggested that typically it would take two days to mobilize contractors and resources and then a base level of access (comparable to the status quo service level) could be restored at an estimated 100 meters per day for repairs. Therefore, within this context, the estimated TfR would consist of the (number of kilometers affected)*10 plus 2 days during which time no repair work commences. Recovery is considered to have been met once service is resumed to the level of service available in the current (Status Quo) alternative, which is lower than the full pre-event levels of service in the upgraded scenarios.

Table 11. Time for Recovery by rain event and road project alternative

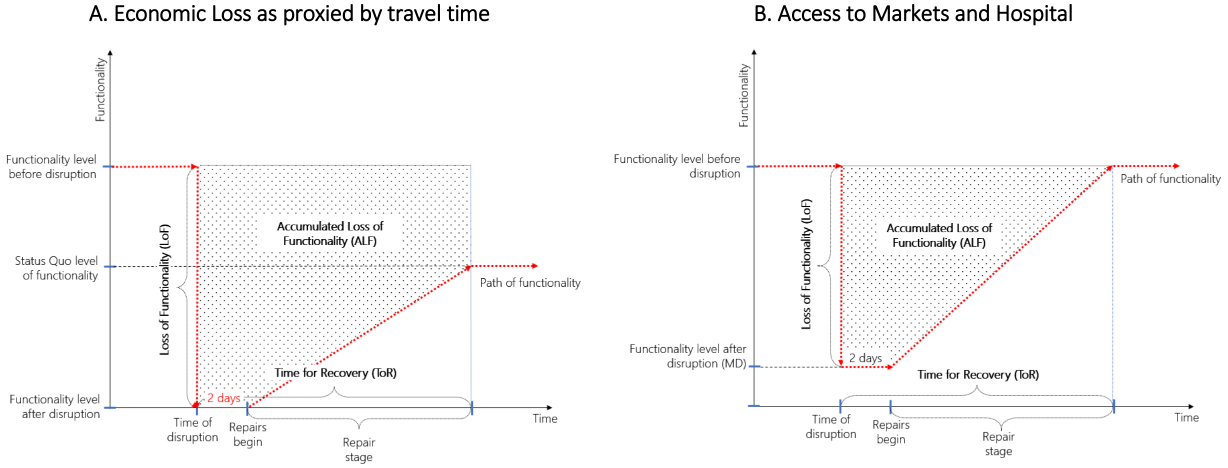
Rainfall Event		SQ	MD	HD	SLS
3-year rain event	Affected length (km)	1.65	0.00	0.00	0.40
	TfR (days)	16.53	0.00	0.00	3.99
10-year rain event	Affected length (km)	2.84	0.73	0.37	1.10
	TfR (days)	28.40	7.27	3.67	10.99
30 -year rain event	Affected length (km)	4.58	2.47	1.93	2.95
	TfR (days)	45.84	24.71	19.32	29.50

IV. Estimating Accumulated Loss of Functionality (ALF)

In order to estimate the accumulated losses of functionality (ALFs) with respect to market access, hospital access, and travel time over the 30-year lifespan of the road, per-event estimated functionality losses were estimated and then summed over the full lifecycle period.

Referring to the mathematical underpinning for calculating ALF, the accumulated losses with respect to travel time, access to markets, and access to hospitals may be conceptualized as the shaded areas in Figure 13 A and B. The two figures are different because first, in the calculation of the economic loss, with road upgradation there is an improvement in the functionality levels (pre-disruption) since travel time is reduced. However, in the case of access to markets and hospital, the functionality in terms of the total number of people with access does not change despite road upgradation. The change occurs in the post-disruption phase, because fewer segments of the road become impassable and therefore, fewer people are impacted and recovery is faster because fewer kilometers of road are damaged. Second, in the former, when there is a disruption, there is zero functionality for 2 days. However, in the latter, post disruption, there are still some people who live with walking distance to Dala and can access services regardless of the disruption to the various segments in the road. Lastly, recovery level in terms of travel time is calculated up to the point it is made passable at the status quo level of functionality, however for access to markets and hospitals, it is the same irrespective of surface type.

Figure 13. Conceptualization of ALF in East Road Case



A. Economic Loss as proxied by travel time

B. Access to Markets and Hospital

Mathematically, therefore, ALF equates to:

1. For economic loss (for upgraded scenarios)[36] -

$$ALF = (FBD \times 2) + (0.5 \times SQF \times TfR\_rs) + ([FBD - SQF] \times TfR\_rs) \qquad (1)$$

2. For access to markets and hospitals

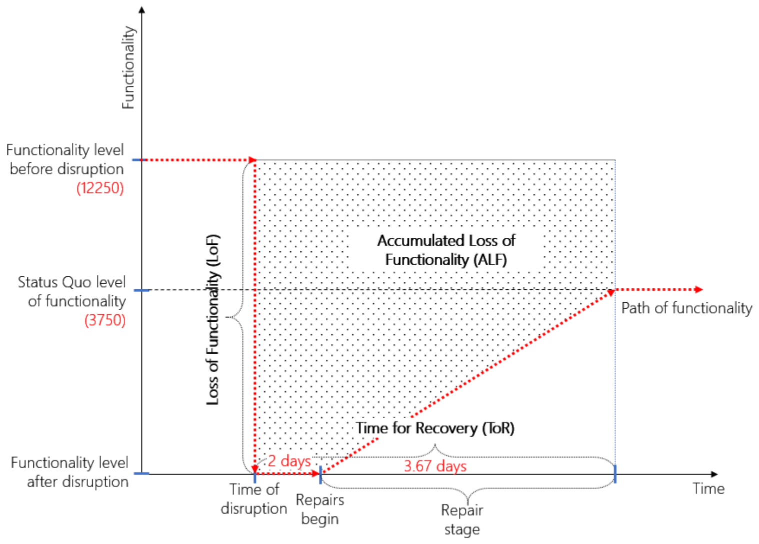
$$ALF = (FBD - FPD) \times ([0.5 \times TfR\_rs] + 2) \qquad (2)$$

FBD denotes the functionality level 'before disruption', *FPD* the functionality level 'post disruption', SQF the 'status quo' functionality level, and *TfR_rs* is the time for recovery during the repair stage.

1. ALF for Economic Loss

Using the functionality levels (i.e. the consumer surplus estimations) calculated in the previous section, the ALF for each scenario was estimated using the relevant TfR detailed in Table 11. An example for the Higher Design scenario under the 10-year rain event is depicted in Figure 14 below. The shaded area represents the ALF and is calculated using formula 1.

Figure 14. ALF for economic loss under HD scenario for 10-year rain event



The ALFs associated with travel time are detailed in Table 12.

Table 12. Estimated ALFs for Travel Time by scenario, rain event, and cumulative ALF for Travel Time

	3-year rain event ALF	10-year rain event ALF	30-year rain event ALF	ALF full lifecycle (30 years)
Scenario 0 (SQ)	38,494	60,750	93,450	660,638
Scenario 1 (MD)	0	65,164	180,704	376,195
Scenario 2 (HD)	0	62,576	224,945	412,674
Scenario 3 (SLS)	50,472	105,072	249,450	1,069,386

---

[36] For SQ – the ALF would be $SQF(2 + [0.5 \times TfR\_rs])$.

2. ALF for Access to Hospitals and Markets

Table 13 shows the results of the ALF calculations for hospital and market access, by event, and then cumulatively over the 30-year lifespan of the road. The calculation is based on formula 2, an example of which (Access to Hospitals under medium design for 10-year rainfall event) is depicted in Figure 15 below.

Figure 15. ALF for Access to Hospitals under MD scenario for 10-year rain event

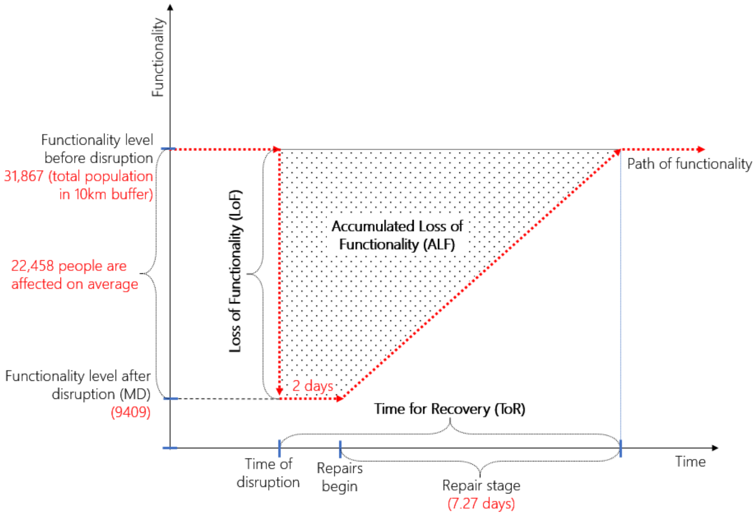


Table 13. Estimated ALFs by event and cumulative over full project lifecycle

ALF for Access to Hospitals

	3-year rain event ALF	10-year rain event ALF	30-year rain event ALF	ALF full lifecycle (30 years)
Scenario 0 (SQ)	229,936	367,270	568,724	3,969,895
Scenario 1 (MD)	0	126,551	327,165	706,817
Scenario 2 (HD)	0	83,703	265,032	516,140
Scenario 3 (SLS)	83,496	167,461	381,130	1,718,467

ALF for Access to Markets

	3-year rain event ALF	10-year rain event ALF	30-year rain event ALF	ALF full lifecycle (30 years)
Scenario 0 (SQ)	86,514	138,219	214,019	1,493,818
Scenario 1 (MD)	0	47,611	123,119	265,950
Scenario 2 (HD)	0	31,520	99,737	194,297
Scenario 3 (SLS)	31,522	62,984	143,416	647,583

V. Estimating Cost for Different Road Designs

In order to estimate the whole lifecycle costs related to each road upgradation scenario, capital costs, maintenance costs as well as repair costs based on damages due to rain events were calculated. Road construction and maintenance data from the Solomon Islands Road and Aviation Project (SIRAP) and the Solomon Islands National Transport Plan 2017-2036 were important sources for cost estimation. This cost information was used by road sector experts to decide on reasonable per-unit (per-km) cost assumptions to be used. Cost data for similar road projects also informed assumptions about per-unit (km) repair costs for each type of road surface subject to various damage levels.

The maintenance costs specified below are for basic routine maintenance for normal road surface wear and tear, not accounting for more significant damages caused by heavy rains and road wash-out. Normal maintenance would be required to clean drains, cut vegetation, patch potholes and minor damages on a regular basis, and to re-gravel or reseal roads periodically. Periodic maintenance would be expected every three to five years for re-graveling and every five to ten years for resealing chip roads. The base cost assumptions associated with road works and their sources are summarized in Table 14. The details of these full cost inputs are included in Annex 1.

Table 14. Roadworks cost assumptions

Road type	Capital Expenditure	Normal Maintenance Expenditure	Cost Source
Gravel	US$50,000/km for gravelling and some improvements to drainage	US$3,000/km per year for routine maintenance US$30,000/km every 3 years for periodic re-gravelling	Existing road contracts in Malaita
Chip seal (BTC)	US$350,000/km for BTC paving	US$3000/km per year for routine maintenance US$150,000/km every 10 years for resealing	SIRAP estimate for capital expenditure Existing road contracts in Malaita for maintenance
Cement concrete	US$500,000/km for concrete paving	US$3000/km per year for routine maintenance US$20,000/km every 10 years for repairs	Expert input

Table 15 provides the details of the cost estimates with annualized operational expenditures. In addition, costs associated with repairs due to 3-, 10-, and 30-year rain events are incorporated to provide the complete lifecycle cost associated with the type of road upgradation.

Table 15. Road Lifecycle Costs, *including repairs for rain events*

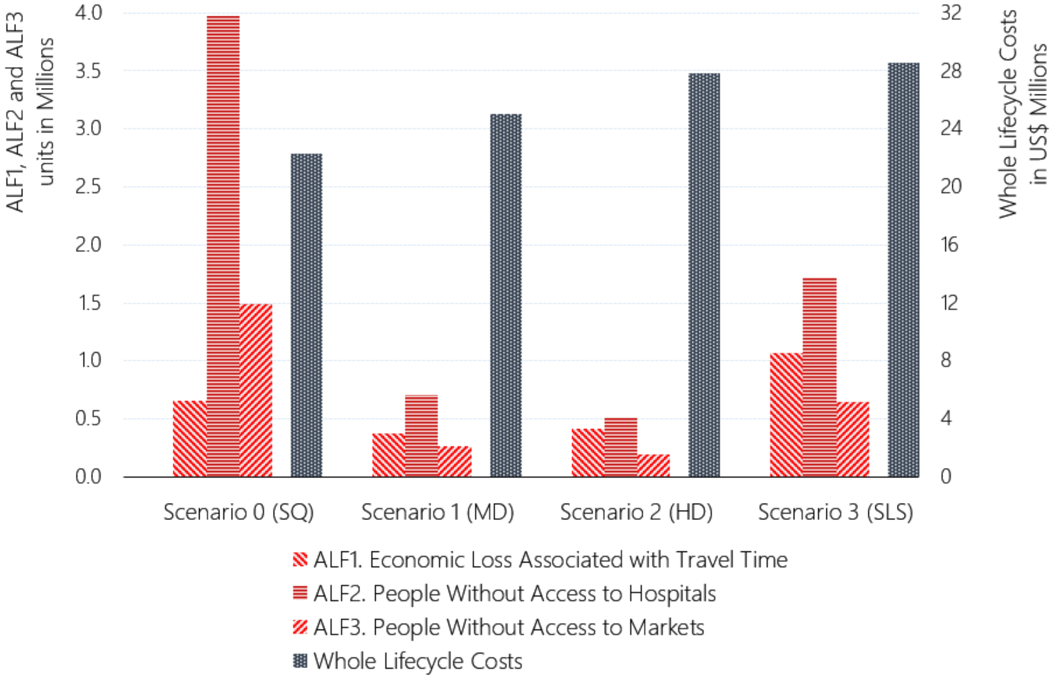
		Kms	Specifications	Unit Cost (US$ per km)		Total Cost *(CAPEX+(OPEX* 30yrs))*Kms*	Estimated Rain Event Repair Costs, 30 years	Whole Lifecycle Cost *(Total Cost + Repair Cost)*
				CAPEX	Annualized OPEX			
0	Status Quo (SQ)	41.533	Gravel, earth drains	50,000	15,000	20,766,500	1,490,603	22,257,103
			Total			**US$20,766,500**	1,490,603	**US$22,257,103**
1	Medium Design (MD)	29.546	Gravel, earth drains (<9%)	50,000	15,000	14,773,000	117,827	14,890,827
		7.335	Chip seal, lined drains (9-15%)	350,000	18,000	6,528,150	641,865	7,170,015
		4.652	Cement concrete, lined drains (>15%)	450,000	5,000	2,791,200	209,342	3,000,542
			Total			**US$24,092,350**	969,034	**US$25,061,384**
2	High Design (HD)	22.355	Gravel, earth drains (<6%)	50,000	15,000	11,177,500	27,944	11,205,444
		14.526	Chip seal, lined drains (6-15%)	350,000	18,000	12,928,140	704,783	13,632,923
		4.652	Cement concrete, lined drains (>15%)	450,000	5,000	2,791,200	209,342	3,000,542
			Total			**US$26,896,840**	942,069	**US$27,838,909**
3	Sealed Long, Steep Sections (SLS)	25.34	Gravel, earth drains	50,000	15,000	12,670,000	312,873	12,982,873
		16.193	Chip seal, lined drains	350,000	18,000	14,411,770	1,168,821	15,580,591
			Total			**US$27,081,770**	1,481,694	**US$28,563,464**

The results show a significant reduction in both disrupted length and resulting repairs costs as a result of paving for slopes over 15% grade. For slopes from 9-15%, the repair cost savings associated with reduced disruptions are offset by the increased costs of repair – i.e., despite the requirement for fewer repairs, the capital expenditures result in a minimal cost difference. This, of course, does not consider other losses associated with road closures (as discussed in the following section). For slopes from 6-9%, there is little reduction in repair costs but some reduction in affected road segment length.

The cost calculations in this report do not account for inflation over the 30-year time period as it is not possible to predict with 100% precision when a rain event would occur during the life span of the road. Consequently, it is possible that the repair costs are under-estimated, since the dollar value in the future is likely to be higher than it is today.

VI. Conclusion and Discussion

Figure 16. ALF over 30 years and costs under each road upgradation scenario



The results of the analysis demonstrate that, while lifecycle costs[37] are lowest for the status quo 'reactive' practice of grading and re-graveling as needed to repair damaged road segments, the accumulated functionality losses of *not upgrading* the current road design, in general, are far higher than the alternative 'proactive' resilient-oriented options (see Figure 16). From a public health and human safety perspective, the improved roads would drastically reduce the accumulated losses associated with hospital access. Similarly, access to markets would be safeguarded at a significantly higher level for the upgraded roads. While improved travel time has direct benefits, additional aspects such as fuel consumption and vehicle maintenance are also likely to reduce with upgradation. Table 16 summarizes the resiliency benefits vis-à-vis the whole lifecycle costs of each road upgradation scenario.

The results for travel time show that the scenario involving sealing only the long steep sections (SLS) would produce the largest the losses. This is driven by two factors – a) the functionality level before disruption is higher than that of SQ and therefore, any disruption generates greater losses (since many more persons

---

[37] As defined in this paper including the financial costs of construction, maintenance, and expected repairs.

were benefitting from the improved road in the first place), and b) despite, sealing steep sections, the SLS scenario faces losses even under the 3-year rain-event. Therefore, the number of persons impacted gets compounded and the loss in terms of travel time and traffic volume gets amplified.

In contrast, given the resilience of the medium and high design to disruptions, despite starting at higher functionality levels than SQ, fewer people are impacted in total due to the greater ability to withstand the rainfall impact. This holds true for all dimensions of functionality studied in this paper. Outside of the travel time functionality, SLS allows greater number of people to retain access to hospitals and markets in times of disruptions when compared to SQ.

Table 16. Resiliency in terms of ALF over 30 years and Costs under each road upgradation scenario

				ALF over 30 years		
Road Project Alternatives	**Segment Length (km)**	**Surface Type**	**Whole Lifecycle Costs (US$)**	**Travel Time**	**Access to Hospitals**	**Access to Markets**
Scenario 0 (SQ)	41.533	Gravel, earth drains	22,257,103	660,638	3,969,895	1,493,818
Scenario 1 (MD)	29.546	Gravel, earth drains (<9% grade)	25,061,384	376,195	706,817	265,950
	7.335	Chip seal, lined drains (9-15% grade)				
	4.652	Cement concrete, lined drains (>15% grade)				
Scenario 2 (HD)	22.355	Gravel, earth drains (<6% grade)	27,838,909	412,674	516,140	194,297
	14.526	Chip seal, lined drains (6-15% grade)				
	4.652	Cement concrete, lined drains (>15% grade)				
Scenario 3 (SLS)	25.34	Gravel, earth drains	28,563,464	1,069,386	1,718,467	647,583
	16.193	Chip seal, lined drains (long, steep segments)				

Compared to the SQ scenario, the whole lifecycle costs increase by 13% for medium design, 25% for high design and 28% for sealing long steep sections. At the same time, the losses decrease by a substantially greater proportion as depicted in Table 17 below.

Table 17. Impact of road upgradation compared with SQ Scenario

		% decrease in ALF (vs SQ)		
Scenario	% increase in cost (vs SQ)	Travel Time	Access to Hospitals	Access to Markets
Scenario 1 (MD)	12.60	-43.06	-82.20	-82.20
Scenario 2 (HD)	25.08	-37.53	-87.00	-86.99
Scenario 3 (SLS)	28.33	61.87	-56.71	-56.65

While the high design option provides the greatest benefits in the long-term, in a context of resource constraint, the most compelling road-upgradation option resulting from the analysis would be the medium design option, since the incremental cost over the entire lifecycle of the road is only 12% and the resulting resiliency benefits are only 5-6 percentage points below the high design scenario. Therefore, it is important to consider the benefits of spending higher amounts, both upfront and over the lifetime of the road, given the long-term benefits it has to the people and the minimization of regular maintenance and repair, especially in the context of climate change. This is also important for low-volume rural roads, such as this one in Malaita, which is often the only way for the people living around it to remain connected to essential services.

It is also important to note that while this study limited itself to the impact of structural/technical road improvements on resilience, there are several other aspects that can influence the ALF. Resiliency benefits can be enhanced by improving contractual methods for road maintenance and repair that can lower the time for recovery. Similarly, the lack of funds for timely maintenance or operating expenditures can cause greater damage than anticipated to any type of road because of the lower ability of a poor-quality road to withstand natural events. Hence, a narrow focus on just technical improvement may not be sufficient to realize the benefits estimated in this paper.

Secondly, secondary effects of road improvement need to be carefully considered and managed in any road intervention project. For instance, Malaita has been heavily logged, with forest losses being as recent as 2019. Therefore, it is important to consider whether a better road network would accelerate the rate of deforestation, which is already ongoing at unsustainable rates, because large vehicles would be able to move faster across the island. Such impacts need to be considered and management plans developed for the same.

This study relied on domain knowledge as a way to compensate for the lack of reliable measurements. This will remain as an area for future improvement. Many of the cost input assumptions are based on expert opinion and data from similar contexts (such as other Pacific Islands), but not the Solomon Islands itself. In addition, the selection of the rainfall event (in the lack of real rainfall data) as well impact of disruption on particular gradients is based on expert opinion. As such, the current analysis serves as an input to decision making that should be considered alongside expert, experience-based guidance. Another limitation of the study is that it is based on elevation data – the results could be further improved with knowledge on drainage and locations of bridges, which are more vulnerable to flooding events.

VII. Technical Annexes

Annex 1. Rain Event Repair Costs

Scenario 0. Status Quo (SQ)

Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption 30 years (km)	Total disruption 30 years (km)	Repair unit cost	Repair total cost	Repair total cost
GR	<6%	22.4	2.5%	0.6	30	0.6	**0.6**	US$50,000	US$27,944	**US$27,944**
GR	6%-9%	7.2	5%	0.4	10	1.1	**1.8**	US$50,000	US$53,930	**US$89,883**
GR	6%-9%	7.2	10%	0.7	30	0.7		US$50,000	US$35,953	
GR	9%-15%	7.3	10%	0.7	3	7.3	**12.1**	US$50,000	US$366,780	**US$605,187**
GR	9%-15%	7.3	15%	1.1	10	3.3		US$50,000	US$165,051	
GR	9%-15%	7.3	20%	1.5	30	1.5		US$50,000	US$73,356	
GR	>15%	4.7	20%	0.9	3	9.3	**15.4**	US$50,000	US$465,205	**US$767,589**
GR	>15%	4.7	30%	1.4	10	4.2		US$50,000	US$209,342	
GR	>15%	4.7	40%	1.9	30	1.9		US$50,000	US$93,041	
Total		**41.5**				**29.8**	**29.8**		**US$1,490,603**	**US$1,490,603**

Scenario 1. Medium Design (MD)

Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years (km)	Total disruption, 30 years (km)	Repair unit cost	Repair cost	Repair total cost
GR	<6%	22.4	2.5%	0.6	30	0.6	**0.6**	US$50,000	US$27,944	**US$27,944**
GR	6%-9%	7.2	5%	0.4	10	1.1	**1.8**	US$50,000	US$53,930	**US$89,883**
GR	6%-9%	7.2	10%	0.7	30	0.7		US$50,000	US$35,953	
BT	9%-15%	7.3	5%	0.4	10	1.2	**1.9**	US$350,000	US$385,119	**US$641,865**
BT	9%-15%	7.3	10%	0.7	30	0.7		US$350,000	US$256,746	
CC	>15%	4.7	10%	0.5	30	0.5	**0.5**	US$450,000	US$209,342	**US$209,342**
Total		**41.5**				**4.8**	**4.8**		**US$969,035**	**US$969,035**

Scenario 2. High Design (HD)

Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years (km)	Total disruption, 30 years (km)	Repair unit cost	Repair cost	Repair total cost
GR	<6%	22.4	2.5%	0.6	30	0.6	**0.6**	US$50,000	US$27,944	**US$27,944**
BT	6%-9%	7.2	2.5%	0.2	30	0.2	**0.2**	US$350,000	US$62,918	**US$62,918**
BT	9%-15%	7.3	5%	0.4	10	1.2	**1.9**	US$350,000	US$385,119	**US$641,865**
BT	9%-15%	7.3	10%	0.7	30	0.7		US$350,000	US$256,746	
CC	>15%	4.7	10%	0.5	30	0.5	**0.5**	US$450,000	US$209,342	**US$209,342**
Total		**41.5**				**3.1**	**3.1**		**US$942,070**	**US$942,070**

Scenario 3. Steep, Long Slopes Design (SLS)

Surface	Slope	Length (km)	Disruption (%)	Disruption (km)	Frequency (years)	Disruption, 30 years (km)	Total disruption, 30 years (km)	Repair unit cost	Repair cost	Repair total cost
GR	<6%	17.1	2.5%	0.4	30	0.4	**0.4**	US$50,000	US$21,341	**US$21,341**
BT	<6%	5.3	N/A	N/A	N/A	N/A		US$50,000	N/A	
GR	6%-9%	3.5	2.5%	0.1	10	0.3	**0.5**	US$50,000	US$13,106	**US$54,180**
GR	6%-9%	3.5	5%	0.2	30	0.2		US$50,000	US$8,737	
BT	6%-9%	3.7	2.5%	0.1	30	0.1		US$350,000	US$32,337	
GR	9%-15%	3.0	5%	0.2	3	1.5	**3.6**	US$50,000	US$75,172	**US$502,796**
GR	9%-15%	3.0	7.5%	0.2	10	0.7		US$50,000	US$33,828	
GR	9%-15%	3.0	10%	0.3	30	0.3		US$50,000	US$15,034	
BT	9%-15%	4.3	5%	0.2	10	0.6		US$350,000	US$227,257	

BT	9%-15%	4.3	10%	0.4	30	0.4		US$350,000	US$151,505	
GR	>15%	1.8	10%	0.2	3	1.8	5.1	US$50,000	US$88,275	US$903,375
GR	>15%	1.8	15%	0.3	10	0.8		US$50,000	US$39,724	
GR	>15%	1.8	20%	0.4	30	0.4		US$50,000	US$17,655	
BT	>15%	2.9	2.5%	0.1	3	0.7		US$350,000	US$252,574	
BT	>15%	2.9	10%	0.3	10	0.9		US$350,000	US$303,089	
BT	>15%	2.9	20%	0.6	30	0.6		US$350,000	US$202,059	
Total		41.5				9.6	9.6		US$1,481,694	US$1,481,694

Annex 2. Methodology for Calculating Affected Population

The East Road runs across wards Fauabu (#4) and Nafinua (#15). The population in these two wards was estimated using distribution data from WorldPop open source data (updated in year 2015). The total population was estimated at 14,700. Using Census data for 2015, the estimated population in wards #4 and #5 would be 13,767, based on an average growth rate between 1999 and 2009. Given that the difference between the two estimation was not significant (as seen in the table below), the WorldPop open source data were adopted as the baseline population layer for the ArcGIS models.

Ward #	Ward Name	Census data (2015)	WorldPop Estimates (2015)
4	Fauabu	9,207	9,858
15	Nafinua	4,560	4,842
	Total Population	**13,767**	**14,700**

With the WorldPop data, the fine-grain level population distribution was established. With a 3-km buffer zone, a total population of 10,648 could potentially be affected potentially with respect to market access, whereas within a 10-km buffer zone, a total population of 31,867 could potentially be affected with respect to access to hospitals.

Using ArcGIS, the East Road was divided into 5,856 segments based on the GIS information provided by the expert (self-collected data using a smartphone were compared with government data and since consistency was found, the former were used as the data input). The Haversine formula was used to determine the length of each segment connecting two points, which was then utilized to calculate the corresponding gradient of the segment. Each segment on average was about 5-10 meters in length. Each segment was then assigned with a numbered ID from east to west. A Python-automated program randomly selected a number of road segments (along the East Road) to be affected by a specified rain event and road upgrading combination. Under each rainfall scenario, each road design's gradient threshold would result in different damage profiles.

By using the random sampling selection method and identifying the nearest segment towards the Dala end of the road that would be hypothetically affected, the maximum affected population within the road buffer zones during road disruption was calculated. This calculation was based on the sum of people within the buffer zone to the east of the west-most affected road segment, minus the sum of people within a 3km/10km (based on the functionality being considered) distance of the west-most affected road segment. The latter was subtracted from the number of affected people because we assume that people within a 3km/10km distance of the west-most disrupted road segment can simply walk across and access the services required. The program was run 100 times for each combination, and the affected population was estimated based on an average of all 100 runs of the analysis.