Sens

Climate Risk and Vulnerability Assessment (CRVA) and Disaster Risk Assessment (DRA)

Priority 1 Bridges

Prepared for Fiji Roads Authority
Prepared by Beca International Consultants Ltd

27 March 2024

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Sensitivity: General

Revision History

Revision Nº	Prepared By	Description	Date
A	Oliver Poynter, Reza Shafiei	Issued for Concept Design	7/02/2023
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Action	Name	Signed	Date
Prepared by	Oliver Poynter		26/03/2024
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Abbreviations, Acronyms and Symbols

ADB	Asian Development Bank
ARI	Annual recurrence interval
AR6	Sixth assessment report
AS	Australian Standard
BICL	Beca International Consultants Limited
BOM	Bureau of Meteorology
CC	Climate change
CMIP	Coupled model intercomparison project
CRVA	Climate risk vulnerability assessment
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CVA	Climate vulnerability assessment
DCLS	Damage control limit state
DRA	Disaster risk assessment
ENSO	El Nino-southern oscillation
FRA	Fiji Roads Authority
GCM	Global climate model
GHG	Greenhouse gases
GTM	Global tsunami model
HAT	Highest astronomical tide
IL	Importance level
IPCC	Intergovernmental Panel on Climate Change
LAT	Lowest astronomical tide
LMMA	Locally-managed marine area
MHWN	Mean high water neaps
MHWS	Mean high water springs
MLWN	Mean low water neaps
MLWS	Mean low water springs
MSL	Mean sea level
MWL	Mean water level
NCEI	National Centres for Environmental Information
ND	Normal Depth
NOAA	National Oceanic and Atmospheric Administration
NZS	New Zealand Standard

NZTA	Waka Kotahi NZ Transport Agency
PACCSAPP	Pacific-Australia climate Change Science and Adaptation Planning Program
PICCAP	Pacific Islands Climate Change Assistance Project
PRIF	Pacific Regional Infrastructure Facility
RCP	Representative concentration pathways
RFI	Request for information
RL	Relative level
SLR	Sea level rise
SLS	Serviceability limit state
SPCZ	South Pacific convergence zone
SPREP	Secretariat of the Pacific Regional Environment Programme
SSP	Shared socioeconomic pathways
TC	Tropical cyclone
ULS	Ultimate limit state
WACOP	Waves and coasts in the pacific
WG	Working group

Executive Summary

Fiji Roads Authority (FRA) has engaged Beca International Consultants Limited (BICL) to provide consulting engineering services for the replacement of 40 bridges and three maritime structures in Fiji. The project is funded through Asian Development Bank (ADB).

The 43 structures have been prioritised into five groups as follows.

- Priority 1 Bridges (10 bridges)
- Priority 2 Bridges (10 bridges)
- Priority 3 Bridges (10 bridges)
- Priority 4 Bridges (10 bridges)
- Maritime Structures (3 jetties)

This report provides a Climate Risk and Vulnerability Assessment (CRVA) and a Disaster Risk Assessment (DRA) for the Priority 1 bridge sites. The purpose of the CRVA and DRA is to understand the existing climatic conditions and natural hazards and assess the potential climate change effects on FRA's Priority 1 bridge sites. This report summarises the relevant existing climatic conditions and natural hazards, and provides design criteria recommendations to address future climate change risk.

Bridge replacement locations will be either at the same location as the existing bridge or on one side of the existing bridge. New bridge alignment options will have different bridge openings, orientations to the waterway and exposure to catchment-based flooding and coastal hazards. The ADB has established CRVA and DRA processes that extend from the initial screening through to detailed assessments and implementation of adaptation and mitigation options for the project. Based on the screening, the main natural hazards posing risks to new bridge alignment options are:

- **Catchment-based flooding**. The effect of flood on new bridge alignment varies depending on bridge opening, skew angle, ground topography and other aspects. Options that allow flexibility in the size of the bridge opening and no or low skew to the waterway are preferred. In addition, options with lesser risk of erosion, scour and debris blockage are favoured.
- **Coastal Hazards.** Alignment options protected by a landmass from direct exposure to wave and storm surge impacts and alignment options with a lesser risk of wave-induced erosion are preferred.
- **Earthquake**. Due to the proximity of bridge replacement alignment options at each site, their exposure to earthquakes is expected to be similar. However, at some sites, geotechnical conditions may vary between options due to a steeply dipping rock face or other variations in ground conditions. Alignments with more favourable ground conditions are preferred. This includes options with less risk of earthquake induced settlement and lateral displacement.

1 Project Description

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This report provides a Climate Risk and Vulnerability Assessment (CRVA) and a Disaster Risk Assessment (DRA) for the Priority 1 bridge sites.

2 Scope of the Assessment

Since 2014 the ADB has required all investment projects to consider climate risk and incorporate adaptation measures in projects at risk from climate change impacts. This is consistent with the ADB's commitment to scale up support for adaption and climate resilience in project design and implementation articulated in the Midterm Review of Strategy 2020: Meeting the Challenges of a Transforming Asia and Pacific (ADB, 2014a)

The Asian Development Bank (ADB) has established a CRVA and DRA process that extends from an initial screening through to detailed assessments and implementation of adaptation and mitigation options for the project (ADB, 2014b).

The purpose of the CRVA and DRA is to understand the existing climatic conditions and natural hazards and assess the potential climate change effects on FRA's Priority 1 bridge sites. The report is structured as follows:

- **Methodology:** summarises the approach to CRVA and DRA, including the overarching methodology and inputs.
- **Setting and Topography:** reviews the location of Priority 1 bridge sites and their topographical features.
- **Existing Climate and Natural Hazards Screening:** reviews the existing climatic conditions and natural hazards that are posing risks to the Priority 1 bridge sites.
- **Climate Change Projections:** summarises relevant climate change projections for Fiji and the Priority 1 bridge sites.
- **Vulnerability Assessment:** determines to what extent FRA's proposed works are vulnerable to natural hazards and climate change effects which includes the initial screening and detailed CRVA.
- **Key Findings:** Summarises the key considerations that should be considered during the bridge design development process.

3 Methodology

3.1 CRVA Scope

CRVA and DRA are conducted following the same methodology. The methodology for conducting an expanded CRVA is provided in Climate Proofing ADB Investment in the Transport Section Initial Experience (ADB, 2014b) and Disaster Risk Assessment for Project Preparation (ADB, 2017). Figure 1 shows the overall steps for CRVA and DRA in ADB invested projects with the first step being preliminary risk screening.

The preliminary screening aims to provide an initial assessment of the level of sensitivity of the structure's location and components to climate variables such as temperature, rainfall and extreme sea levels. The screening also includes natural hazards comprising of geophysical hazards such as earthquakes and tsunamis as well as hydrometeorological or extreme weather hazards such as floods, droughts, and tropical cyclones. If the screening identifies any medium or high risks, an incorporated climate risk vulnerability and disaster risk assessment are required in the form of an expanded CRVA and DRA.

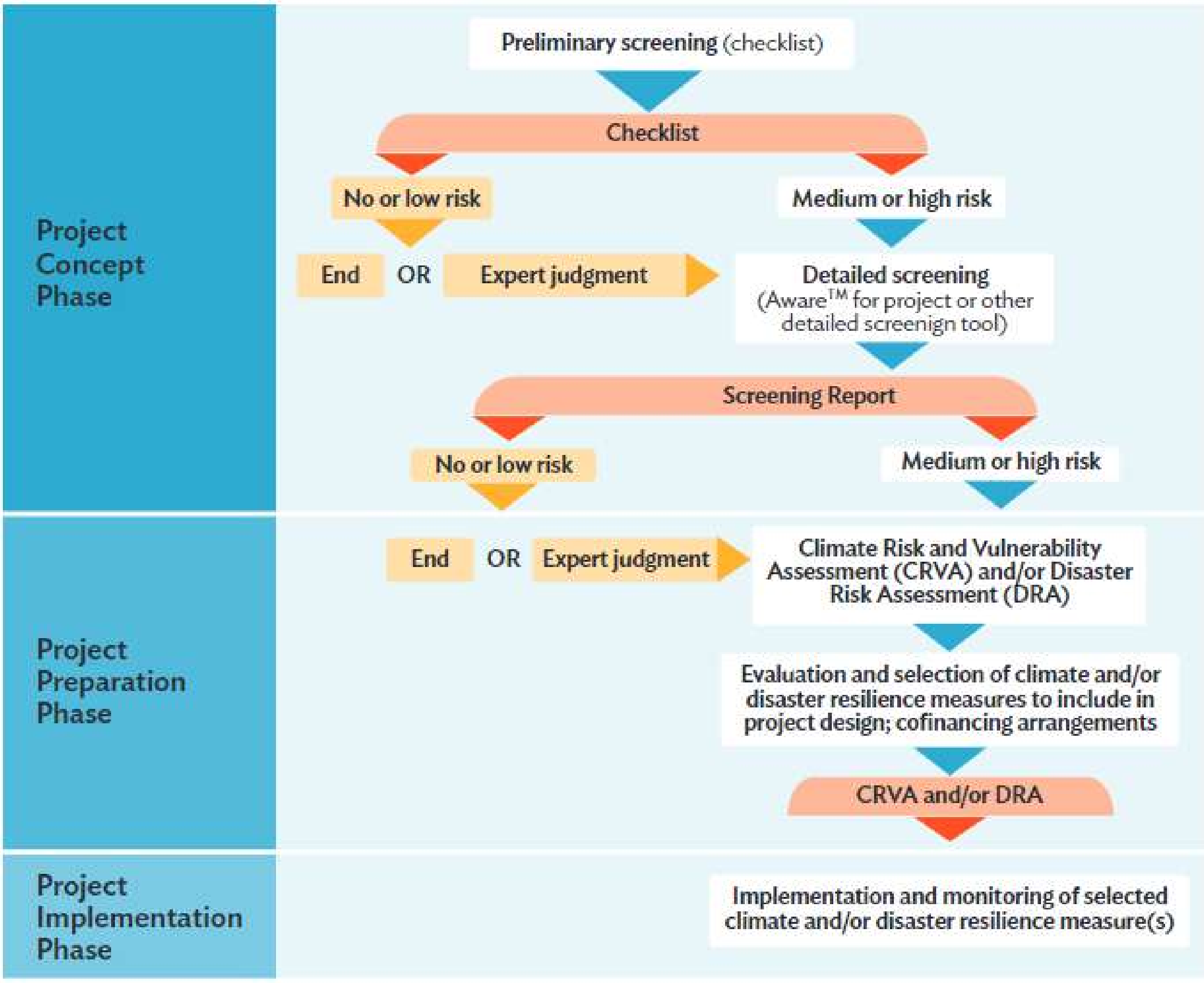

Figure 1: Flow Chart for Climate and Disaster Risk Management of Investment Project (ADB (2017))

The second step is a detailed risk screening of the identified medium and high risks, while still a screening process it aims to detail further the specific nature of climate and disaster risks. The assessment aims to quantify risks and identify adaptation options that can be integrated into the project design. ADB (2014a) notes the level of detail to which the assessment extends is generally dictated by the complexity of the project, available information on the project, available hazard and climate data and projections for the project site.

3.2 Inputs to CRVA and DRA

The Priority 1 Bridges CRVA and DRA includes a review of the existing climate and disaster exposure, followed by the identification of existing hazards. The existing climate is categorised by temperature, rainfall, stream profile, tides, extreme sea levels, wind and waves.

Catchment-based flooding, landslides, extreme weather, tropical cyclones, coastal erosion, coastal flooding, earthquake and tsunami categorise the existing hazards.

To inform the assessment of the identified climate and hazard categories, this CRVA and DRA has used inputs from a range of sources, with the key resources shown in Table 3.1.

Table 3.1: Key resources

Resource	Project Specific (Y/N)	Level of Detail	Hazard
Site specific hydraulic modelling produced by Beca	Y	Detailed analysis	Catchment-based flooding, riverbank erosion and debris loading potential.
MetOcean Solutions (2022): Metocean Study – Fiji jetty design	Y	Detailed analysis for the three jetties.	Wave impact and storm tide flooding.
Detailed Topographical Survey and water level data (FRA, 2022), refer to Appendix A.	Y	Site specific survey	Water based hazards.
McInnes (2014): Quantifying storm time risk in Fiji due to climate variability and change	N	Fiji wide modelling at various locations	Extreme sea level and storm tide flooding.
PRIF (2022) Guidance for Managing Sea Level Infrastructure Risk in Pacific Island Countries	N	Detailed guidance for Pacific Island Countries	Sea level rise.
Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) (2022)	N	Detailed global climate change projections.	Climate change hazards.
ADB (2021) Accounting for Changes in Extreme Daily Rainfall Intensity in Pacific Island Countries	N	Detailed guidance for Pacific Island Countries	Rainfall intensity.
Fiji (2017) Climate Vulnerability Assessment	N	CVA for Fiji	General information on climate hazards impacting Fiji.
PACCSAP (2014) Climate Variability, Extremes and Change in the Western Tropical Pacific	N	Climate information for Fiji.	Current and future climate for Fiji.
CSIRO and SPREP (2021) ‘NextGen’ Projections for the Western Tropical Pacific	N	Climate information for Fiji.	Current and future climate for Fiji.

3.2.1 Limitations

There are a number of limitations to this assessment:

- The incompleteness of the available measured and projected climate data.
- The high levels of uncertainty in climate change models, particularly for the key climate hazards.

These limitations must be appreciated when considering the impacts of climate change and potential adaptation measures within the design process.

3.3 Design Criteria

Consistent with the FRA Bridge Design Manual (FRA, 2015) and Waka Kotahi NZTA Bridge Manual (NZ BM, 2018) the Priority 1 bridges are considered to have an importance level of 3. The Design Criteria Bridges Priority 1 (Beca, 2022) outlines the environmental loading design criteria for the respective bridges and is summarised in Table 3.2.

Table 3.2 Design Criteria Relevant to CRVA and DRA

Design element	Importance Level 2[1]	Importance Level 3[1]	Temporary (IL3) [1]
Bridge design life (years)	100	100	<5
ULS[2]: Flood event	500-year ARI	1000-year ARI	500-year ARI
ULS: Sea level	500-year ARI	1000-year ARI	500-year ARI
DCLS[4]: Earthquake	500-year ARI	1000-year ARI	500-year ARI
SLS1[3]: Design flow	25-year ARI	25-year ARI	25-year ARI
Soffit level	Total waterway to pass the Average Recurrence Interval (ARI) flood corresponding to SLS2 + 0.6m freeboard.	Total waterway to pass the Average Recurrence Interval (ARI) flood corresponding to SLS2 + 0.6m freeboard.	Total waterway to pass the Average Recurrence Interval (ARI) flood corresponding to SLS1 + 0.6m freeboard[5].
SLS2[3]: Flood event	50-year ARI	100-year ARI	N/A
SLS2: Sea level	50-year ARI	100-year ARI	N/A
SLS2: Flood and tidal combined	20-year ARI design flow + 20-year ARI design sea level	20-year ARI design flow + 20-year ARI design sea level	N/A
Climate change	100-year sea level rise 100-year change in daily rainfall intensity	100-year sea level rise 100-year change in daily rainfall intensity	N/A
Scour and Erosion: Design life	50	50	<5
Scour and Erosion Protection: Design flow	100-year ARI	100-year ARI	25-year ARI

Notes:

1. Bridge importance level as derived from Waka Kotahi NZTA Bridge Manual.
2. Ultimate Limit State (ULS): the state beyond which the strength or ductility capacity of the structure is exceeded, or when it cannot maintain equilibrium and becomes unstable.
3. Serviceability Limit State (SLS): The state beyond which a structure becomes unfit for its intended use through deformation, vibratory response, degradation or other operational inadequacy. Both structure and non-structural elements shall remain undamaged following wind and flood events up to an SLS1 event and shall remain operationally functional for all highway traffic during and following flood events up to an SLS2 event.
4. Damage Control Limit State (DCLS): After exposure to a seismic event of design severity, the structure shall be usable by emergency traffic within three days, although damage may have occurred, and some temporary repairs may be required to enable use by vehicles.

Design element	Importance Level 2[1]	Importance Level 3[1]	Temporary (IL3) [1]
5. Bridge Manual does not specify soffit requirements for temporary bridges. For operational purpose, it is recommended to provide 0.6m freeboard above SLS1 water level for temporary bridges.			

4 Setting and Topography

4.1 Geographical Location

The Priority 1 Bridge Sites are located on the 470km ring road encircling the Fijian Island of Viti Levu (Figure 2). The bridge sites are located throughout the western division (8 bridges) and central division (2 bridges), refer to Table 4.1. Table 4.2 provides a geographic description for each site.

Table 4.1 Location of Priority 1 Bridge Sites

Bridge ID (FRA)	Name	Importance Level	Latitude	Longitude	Administrative Division	Provence
2905	Medraukutu Bridge	3	-18.106034°	178.389097°	Central	Rewa
2904	Lami Bridge	3	-18.116583°	178.412335°	Central	Rewa
1602	Navutu Bridge	3	-17.613982°	177.433402°	Western	Ba
1104[1]	Vunitogoloa Bridge	3	-17.362725°	178.052403°	Western	Ra
1415	Visesei Bridge	3	-17.691500°	177.420400°	Western	Ba
1107[1]	Vitawa Bridge	3	-17.369325°	178.110934°	Western	Ra
1616	Navola Bridge	3	-18.231248°	177.764341°	Western	Nadroga / Navosa
1405[1]	Matawalu Bridge	3	-17.616314°	177.439197°	Western	Ba
1419	Sabeto Bridge	3	-17.704800°	177.436000°	Western	Ba
1416	Lomolomo Bridge	3	-17.718902°	177.416660°	Western	Ba

Notes:

1. Temporary bridges will be required at these locations during construction.

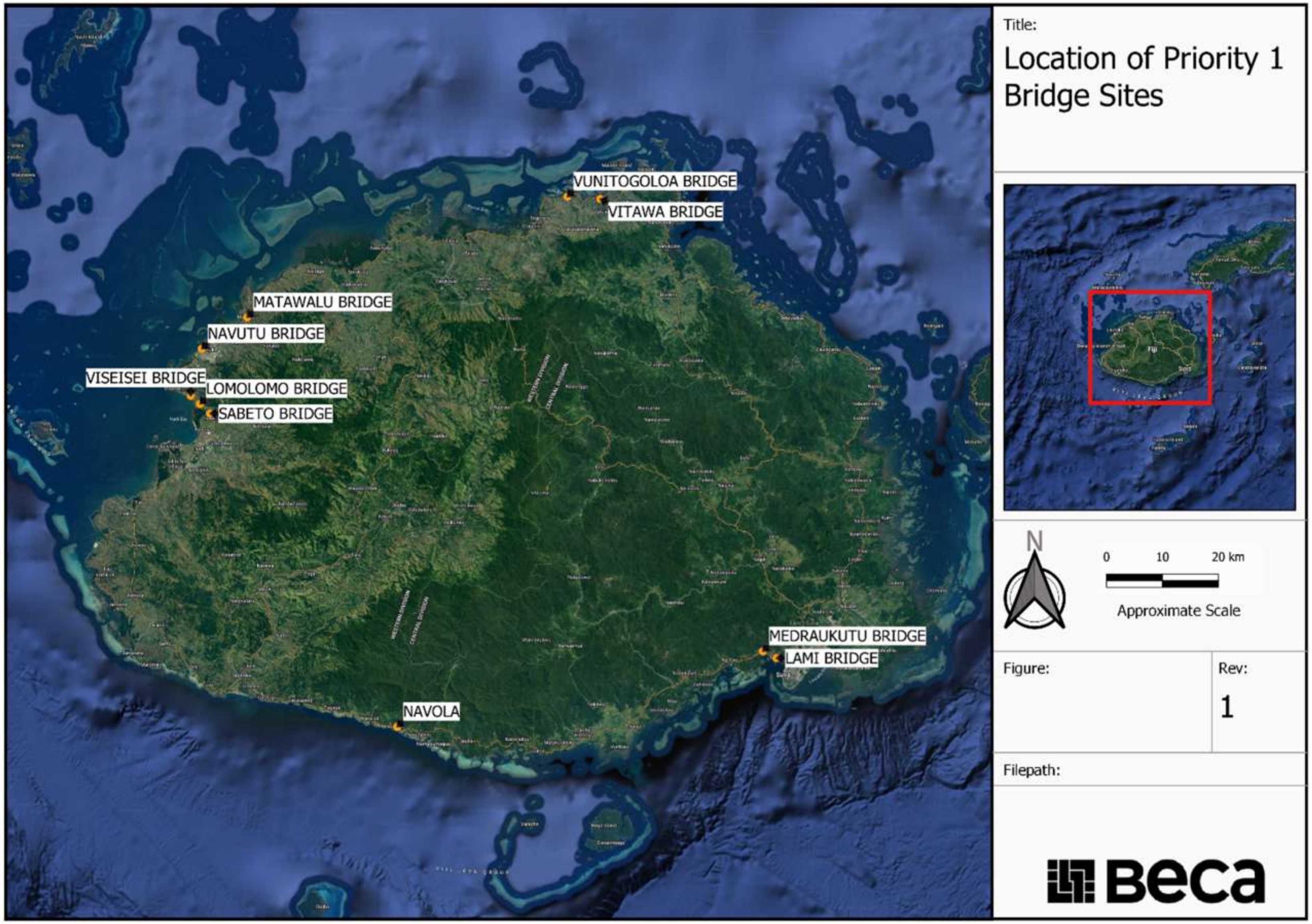

Figure 2: Location of Priority 1 Bridge Sites on Viti Levu, Fiji

Table 4.2 Site Description

Bridge ID	Name	Site Description
2905	Medraukutu Bridge	Located in an urban area approximately 7km west from Suva where Queens Road crosses a tidal channel next to Pacific Cement plant. The bridge is approximately 65m long and the approach roads are low-lying. There are no nearby alternative routes if Medraukutu Bridge is closed. The bridge is on the northern boundary of Draunibota Bay and is fronted by shallow mud sand intertidal flats. The bridge is protected from offshore waves but is potentially exposed to wind waves generated over 3-4km fetch within the bay. The bridge crosses a tidal channel that has a catchment area of 5.5km^2 which outlets into the Vueti Navakavu Locally Managed Marine Area (LMMA).
2904	Lami Bridge	Located in an urban area approximately 4km west from Suva where Queens Road crosses the Lami River between Suvavou Village and Lami. The bridge is approximately 52m long and the approach roads are low-lying. There are no nearby alternative routes if Lami Bridge is closed. The bridge is on the boundary of Suva Harbour and is fronted by shallow mud sand intertidal flats on the fringe of the deeper harbour. The bridge is located directly in line with the navigable entrance to Suva Harbour. Offshore waves are only able to reach the bridge during high tides and will be depth limited by the intertidal flats. The bridge cross Lami River which has a catchment area of 20.8km^2 and is tidal at the bridge site.
1602	Navutu Bridge	Located in an urban area on the southern extent of Lautoka where Navutu Road crosses Musuniwai Creek. The bridge is approximately 19m long and the approach roads are low-lying. There is a ~2.0km detour using Kings Road if the bridge is closed. The bridge is approximately 360m upstream from the coastline and is sheltered from open coast waves. Musuniwai Creek has a catchment area of 3.8km^2 and is tidal at the bridge site.
1104	Vunitogoloa Bridge	Located in a rural area approximately 11km west from Vaileka where Kings Road crosses Wailevu Creek at Vunitogoloa village. The bridge is approximately 27m long and the approach roads are low-lying. There are no nearby alternative routes if Vunitogoloa Bridge is closed. The bridge is approximately 600m upstream from the coastline and is sheltered from open coast waves. Wailevu Creek has a catchment area of 8.91km^2 and is not influenced by present day spring tides at the bridge site.
B4	Vunitgoloa Temporary Bridge	Temporary bridge will be located either upstream or downstream of the permanent works.
1415	Viseisei Bridge	Located in a rural area on the southern extent of Viseisei where Queens Road crosses the Vuda River. The bridge is approximately 75m long and the approach roads are low-lying. There is a ~13km detour using Vuda Back Road and Viseisei Back Road if the bridge is closed. The bridge is approximately 340m upstream from the coastline and is sheltered from open coast waves. Vuda River has a catchment area of 57.85km^2 and is tidal at the bridge site. A rail bridge crosses the river at the same point immediately downstream of the road bridge.
1107	Vitawa Bridge	Located in a rural area approximately 4km west from Vaileka where Kings Road crosses Naveseri Creek at Vitawa village. The bridge is

Bridge ID	Name	Site Description
		approximately 13m long and the approach roads are low-lying. There are no nearby alternative routes if the bridge is closed. The bridge is approximately 700m upstream from the coastline and is sheltered from waves. Naveseri Creek has a catchment area of 3.67km^2 and is not influenced by present day spring tides at the bridge site. The creek discharges into Rakiraki District LMMA.
B6	Vitawa Temporary Bridge	Temporary bridge will be located either upstream or downstream of the permanent works.
1616	Navola Bridge	Located in a rural area approximately 1.5km west from Namatakula where Queens Road crosses Navola Creek. The bridge is approximately 10m long. The western approach road is higher than the bridge and is close to the coastline. There are no nearby alternative routes if Navola Bridge is closed. The bridge is less than 100m inland from the coastline, which is fronted by a fringing reef. Some wave propagation may be possible up the river channel, but likely to be minor. The creek has a catchment area of 4.35km^2 and discharges into Biausevu/Navola/ Vanua Komave-Komave/Namatakula LMMA.
1405	Matawalu Bridge	Located in an urban area where Kings Road crosses the Teidamu Creek at the village of Nathova, approximately 9km north of Lautoka. The bridge is approximately 46m long and the approach roads are low-lying. There is a ~5.5km detour if the bridge is closed. There is a tramline downstream of the bridge. The bridge is approximately 1km from the coast but 3.5km upstream from the creek mouth and is sheltered from open coast waves. The creek has a catchment area of 69.65km^2 and is tidal at the bridge site.
B8	Matawalu Temporary Bridge	Temporary bridge will be located either upstream or downstream of the permanent works.
1419	Sabeto Bridge	Located in a rural area approximately 3.5km north of Nadi Airport where Queens Road crosses the Sabeto River. A rail bridge crosses the river at the same point immediately downstream of the road bridge. The bridge is approximately 86m long and the approach roads are above the surrounding floodplain. There are no nearby alternative routes if the bridge is closed. The bridge is approximately 1.2km inland from the coast but 6.1km upstream from the river mouth and is sheltered from open coast waves. The river has a catchment area of 88.87km^2 and is tidal at the bridge site.
1416	Lomolomo Bridge	Located in a rural area approximately 6.5km north of Nadi Airport where Queens Road crosses Balesasa Creek. A rail bridge crosses the river at the same point immediately downstream of the road bridge. A water control structure is located approximately 1km downstream of the bridge. The bridge is approximately 6m long and the approach roads are above the surrounding floodplain. There are no nearby alternative routes if the bridge is closed. The bridge is approximately 3.2km upstream from the coastline and is sheltered from open coast waves. The creek has a catchment area of 3.60km^2 and is tidal at the bridge site.

4.2 Topography and Bathymetry

The Fijian Island of Viti Levu is approximately 146 kilometres long and 106 kilometres wide and has an area of 10,389 square kilometres. The island is divided into roughly equal halves by a mountain range that runs north to south, with Mount Tomanivi rising to 1,324 metres. The eastern side of the island experiences heavy rainfall, particularly in the mountains. The main river systems, the Rewa, Navua, Sigatoka, and Ba, all have their headwaters in the central mountain area and cross fertile low-lying coastal plains that lie at the foot of the mountains. Much of Fiji's urban and agricultural land is in these areas, including the 10 Priority Bridges.

The coastal plain is composed of a zone of sandy or rocky beach on the seaward edge and a beach ridge or foredune, behind which is either relatively flat ground or, in some places, low-lying depressions or small lagoons filled with brackish water. Coastal ecosystems include mangroves, algae and sea-grass beds in shallow reef and lagoon areas, and various reef types such as barrier, fringing platforms and atoll or patch reefs (PICCAP 2005). Offshore from Viti Levu coast the seabed descends to 20-50 m depths within reef-sheltered harbours (e.g. Suva Harbour, Nadi Bay) but often with numerous shallow reef features.

Fiji's diverse coral reef system includes fringing reefs, barrier reefs, platform reefs, oceanic ribbon reefs, drowned reefs, atolls and near-atolls, forming an estimated 10,000km^2 of coral reefs (Zann, 1992). The width of the fringing reefs around Viti Levu reaches up to 4,000m from the shore in places, and beyond the reef, the seabed drops away from the fringing reefs to 1000's of metres deep.

Although all the Priority 1 bridge sites are located on Viti Levu's coastal ring road, most are positioned several hundred metres upstream from open water except Medraukutu bridge and Lami Bridge which are on the coastal fringe of Draunibota Bay, Suva.

In the absence of definitive Fiji Vertical Datum benchmarks at each site local datums have been determined by water level monitoring at each site, refer to appendix A. Water level monitoring was used to determine a local Mean Sea Level (MSL) datum at each bridge as a benchmark for the works (refer to Table 5). This is further discussed in section 5.1.4.

Table 4.3 Existing Bridge Levels Relative to Local MSL, at the Lowest Section of the Bridge

Bridge ID	Name	Existing Deck Level (mMSL)	Existing Soffit Level (mMSL)	Approximate Superstructure Depth[1] (m)
2905	Medraukutu Bridge	3.4	2.1	1.3
2904	Lami Bridge	4.3	3.5	0.8
1602	Navutu Bridge	5.3	4.8	0.5
1104	Vunitogoloa Bridge	2.6	1.9	0.7
1415	Visesei Bridge	2.5	1.5	1.0
1107	Vitawa Bridge	3.4	2.6	0.8
1616	Navola Bridge	3.5	2.8	0.7
1405	Matawalu Bridge	5.2	4.2	1.0
1419	Sabeto Bridge	4.8	4.0	0.8
1416	Lomolomo Bridge	2.2	1.0	1.2

Notes:

1. Depth derived from difference between existing deck level and soffit level.

5 Climate and Natural Hazards

5.1 Existing Climate

The climate of Fiji is generally categorised as an oceanic tropical climate in which the dry season is from May to October and rainy season is from November to April. Fiji's relative location strongly influences seasonal and interannual variations in climate, particularly rainfall, where the south-easterly tradewinds carry moist air into the islands (PICCAP, 2005). Fiji is also prone to El Niño events and tropical cyclones relative to the positioning of the South Pacific Convergence Zone (SPCZ).

Fiji's climate varies considerably from year to year due to the El Niño-Southern Oscillation (ENSO). This is a natural climate pattern that occurs across the tropical Pacific Ocean and affects weather around the world. There are two extreme phases of the ENSO: El Niño and La Niña. There is also a neutral phase. In Fiji, El Niño events tend to bring dry seasons that are drier and cooler than normal, while La Niña events usually bring wetter than normal conditions (PICCAP, 2005).

5.1.1 Temperature

Temperatures in Fiji remain relatively constant throughout the year, averaging around 23°C - 25°C in the dry season (May-October) and 26°C - 27°C in the wet season (November-April). Greater seasonal variation is seen in the precipitation regime, with an average of around 250-400mm of rainfall per month in the wet season and 80-150mm per month in the dry.

Across Fiji, the annual average temperature is between 20-27°C. Changes in the temperature from season to season are relatively small and strongly tied to changes in the surrounding ocean temperature.

During an ENSO event, conditions drier and hotter than normal can be expected from June to August. During the November–April wet season, Fiji is normally traversed by tropical cyclones as it lies directly in their normal path (PICCAP, 2005).:

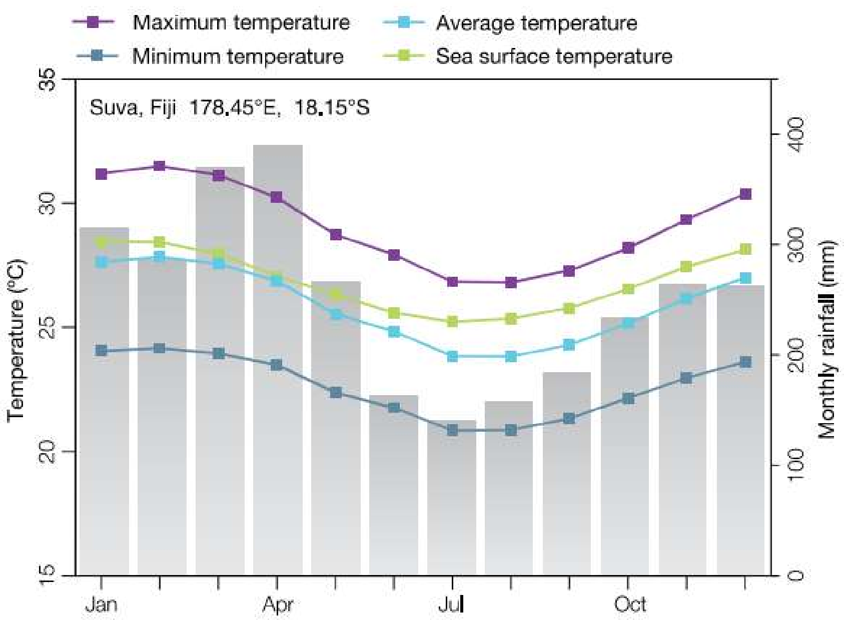

Figure 3: Seasonal Rainfall and Temperature at Suva (PACCSAP, 2014)

5.1.2 Rainfall

Much of Fiji's rainfall is associated with the movement of the SPCZ which is closest to Fiji in the wet season. Annual precipitation shows some spatial variation and Viti Levu sees much stronger precipitation on its east side (3,000-5,000mm) compared to its west (2,000-3,000mm) as the mountains shelter the western lowlands. While the prevailing tradewinds are from the southeast, tropical cyclones and depressions tend to track from the north and west. Thus, although the west of Viti Levu is drier on average, it can experience heavy rainfall events and associated flooding.

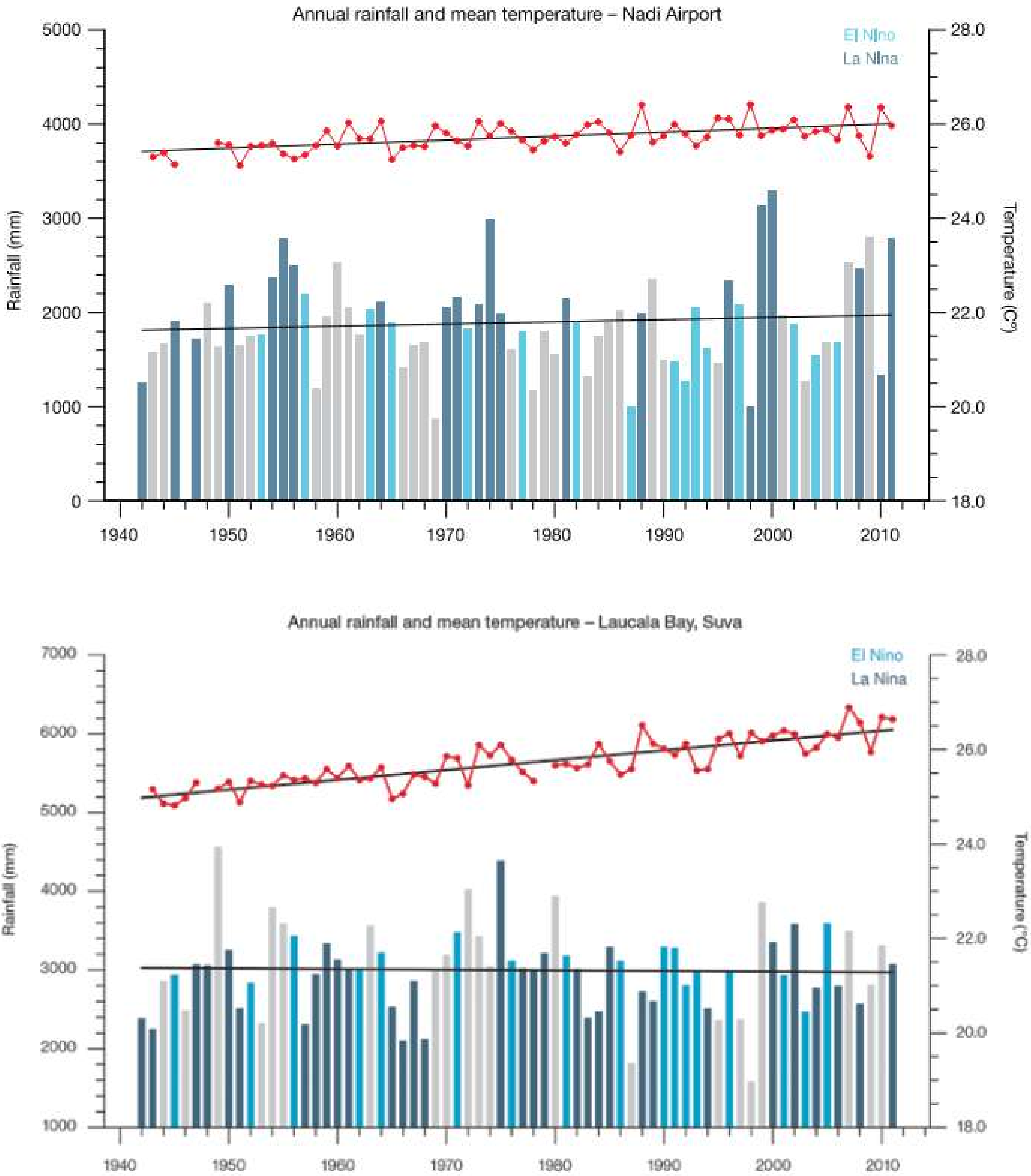

Figure 4: Annual Average Air Temperature (Red Dots and Lines) and Total Rainfall. Light Blue, Dark Blue and Grey Bars indicate El Nino, La Nina and Neutral Years Respectively (PACCSAP, 2014)

5.1.3 Drought

Most droughts in Fiji are associated with ENSO event but not all ENSO occurrences lead to droughts. The impact of drought can be significant in Fiji which include a decrease in agricultural production, mortality of livestock, lack of drinking water and wildfire breakouts. Since 1940, ten significant droughts, were recorded in Fiji (Rhee & Yang, 2018). The economic impact of the damage caused by Fiji's drought in 1998 was estimated between F$275 million and F$300 million (Government of the Republic of Fiji, 2017). The 1998 drought reached a level, which led to the declaration of a national emergency and is estimated to have affected 220,000 people across the country (Fact Sheet – Drought and Health – MHMS. (n.d.). Although significant droughts have occurred severely affecting the country, there are no reports of droughts impacting civil infrastructure.

5.1.4 Tide Levels

The tides within Fijian Archipelago are classified as mixed semi-diurnal. Measured water levels are available from the Bureau of Meteorology (BoM) station at Lautoka on the west coast of Viti Levu (177.4381, -17.6053) from 1st October 1992 – 31st December 2021 and Suva in the south of Viti Levu (178.422839, -18.135678). Hourly measurements of water level, residual water level, adjusted residual water level (adjusted for the effect of static barometric pressure, to be the residual only from wind and wave), wind speed, wind gust, wind direction and atmospheric pressure are available as well as air and sea temperature. The tidal planes in Fiji are described in the Fiji Nautical Almanac (Hydrographic Office of Fiji, 2021).

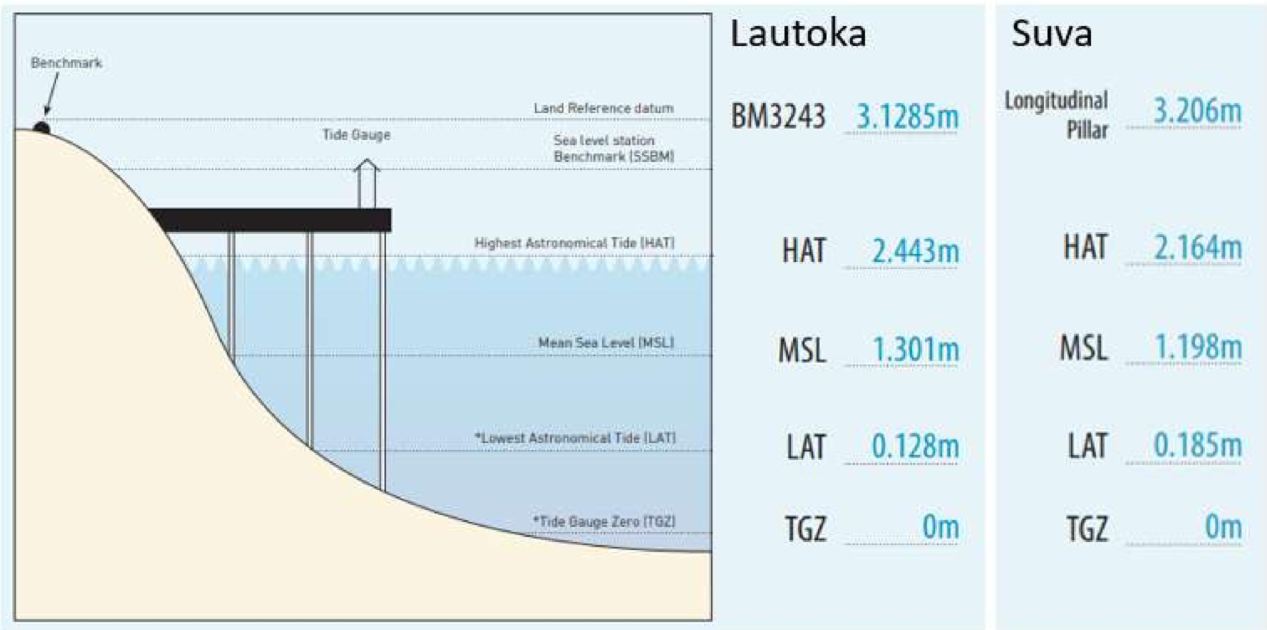

Figure 5: Tidal Definitions in Fiji (BOM, 2021 and BOM, 2022)

The almanac values are determined based on long-term tide measurements at the ports of Suva and Lautoka. The nearest almanac station to each bridge site is shown in Table 5.1 relative to the locally derived MSL datum.

Table 5.1 Locally Derived Mean Sea Level Datum (m MSL). Tide Levels from Fiji Nautical Almanac 2021 (Hydrographic Office of Fiji, 2021).

Bridge ID	Name	Almanac Station	MSL[1]	MHWS	MHWN	MLWN	MLWS
2905	Medraukutu Bridge	Suva	0.56	1.26	1.06	0.06	-0.14
2904	Lami Bridge	Suva	0.23	0.93	0.73	-0.27	-0.47
1602	Navutu Bridge	Lautoka	0.84	1.69	1.39	0.39	0.09
1104	Vunitogoloa Bridge	Manava Cay	0.83	1.58	1.28	0.38	0.08

Bridge ID	Name	Almanac Station	MSL[1]	MHWS	MHWN	MLWN	MLWS
1415	Visesei Bridge	Vuda Point	0.26	0.99	0.79	-0.31	-0.51
1107	Vitawa Bridge	Manava Cay	1.71	2.46	2.16	1.26	0.96
1616	Navola Bridge	Rukua	1.10	1.66	1.56	0.66	0.56
1405	Matawalu Bridge	Lautoka	0.21	1.06	0.76	-0.24	-0.54
1419	Sabeto Bridge	Vuda Point	0.04	0.77	0.57	-0.53	-0.73
1416	Lomolomo Bridge	Vuda Point	0.29	1.02	0.82	-0.28	-0.48

Notes:

1. Locally derived Mean Sea Level for each bridge site.
2. Values based on Fiji Nautical Almanac and adjusted using locally derived MSL.

5.1.5 Historic Sea Level Rise

Recorded monthly mean sea levels and linear rates of change for Fiji relative to local ground levels are presented in Figure 6. The benefit of absolute measurements of mean sea level is that they capture both sea level rise and vertical land movement.

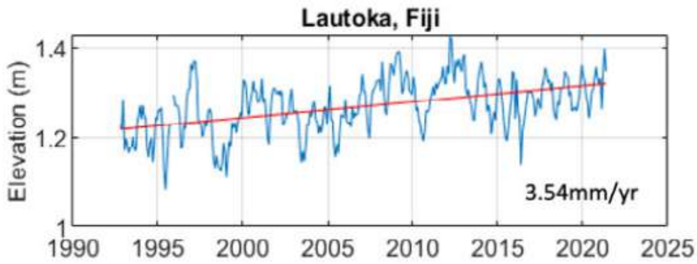

Figure 6: Monthly mean level for Suva based on recorded data (blue line) and resulting linear trend (red line) (PRIF, 2022)

The observed sea level change at the Lautoka tide gauge reveals a historical sea level rise of 3.54mm/year which includes an estimated land subsidence of -1.0mm/year (PRIF, 2022), noting subsidence at the tide gauge of up to -1.1mm/year has been observed since 2002.

5.1.6 Extreme Sea Levels

Extreme water levels are those caused by a combination of tidal and non-tidal processes. The non-tidal processes include storm surge, wave setup and sea level anomalies which relate to tropical cyclones, climate patterns (e.g. ENSO) and the interaction of these with local bathymetry.

McInnes (2014) assessed extreme sea levels at Viti Levu and Vanua Levu in Fiji, forced by stochastically generated cyclones, to estimate storm tide risk around the coastline. The study uses a baseline case that represents cyclones over a 20-year observation period. It provides insight into how storm tide risk is affected by changes in cyclone tracks associated with La Nina and El Nino and how climate change may further modify storm tide levels. Storm tide risk was generally higher on the northwest coastlines than elsewhere owing to both the shallower bathymetric depths and the tendency for cyclones to approach Fiji from the north and west more frequently.

McInnes (2014) noted that their extreme sea levels do not include the influence of wind wave-breaking processes on storm tides. Dissipation of storm waves can lead to considerably higher coastal sea levels and potential for inundation due to wave setup and wave run-up, particularly along coasts bordered by narrow fringing reefs, where wave setup may be up to 30% of incident wave height. However, the shallow shelves, islands and barrier reefs surrounding much of Viti Levu and Vanua Levu would tend to dissipate wave energy offshore, thus having a relatively minor influence on storm tide levels at the coast. However, this may not be the case where near-shore fringing reefs form a barrier between the coast and deep water, such as southern Viti Levu. The omission of waves in the study mean that levels the McInnes (2014) reported results are slightly underestimated at sheltered locations (e.g. most bridge sites) but may be significantly underestimated where exposed fringing reefs closely border coastlines (e.g. Medraukutu and Navola).

Table 5.2 Estimates of Storm Tide Heights (Excluding Effects of Waves) during Baseline Conditions (McInnes, 2014). Relative to local MSL.

Bridge ID	Bridge Name	Ref. location	10-year[1]	20-year	50-year	100-year	500-year	1000-year
2905	Medraukutu	Suva	1.34	1.42	1.65	1.78	2.01	2.09
2904	Lami	Suva	1.01	1.09	1.32	1.45	1.68	1.76
1602	Navutu	Lautoka	1.80	2.1	2.59	2.94	3.68	3.99
1104	Vunitogoloa	Lautoka[2]	1.71	2.09	2.58	2.93	3.67	3.98
1415	Visesei	Nadi	1.02	1.44	1.9	2.23	2.99	3.3
1107	Vitawa	Lautoka[2]	2.59	2.97	3.46	3.81	4.55	4.86
1616	Navola[3]	Suva	1.89	1.96	2.19	2.32	2.55	2.63
1405	Matawalu	Lautoka	1.17	1.47	1.96	2.31	3.05	3.36
1419	Sabeto	Nadi	0.8	1.22	1.68	2.01	2.77	3.08
1416	Lomolomo	Nadi	1.05	1.47	1.93	2.26	3.02	3.33

Notes:

1. Values are extrapolated from McInnes (2014)
2. Vunitogoloa and Vitawa are likely to have smaller extreme sea level based on the location compared to the reference location of Lautoka.
3. Although Suva is the closest reference location the reported storm tide heights may be underestimated as Navola is closely boarded by fringing reefs.

5.1.7 Wind

Typical wind speeds vary based on trade winds, southern storms, cyclones and the location of the SPCZ. The prevailing winds over Fiji are typically south-easterly with the highest monthly mean wind speeds occurring in July reaching approximately 5m/s. Figure 7 and Figure 8 show typical wind rose and seasonality winds for the South (Suva) and West (Denauru) coasts.

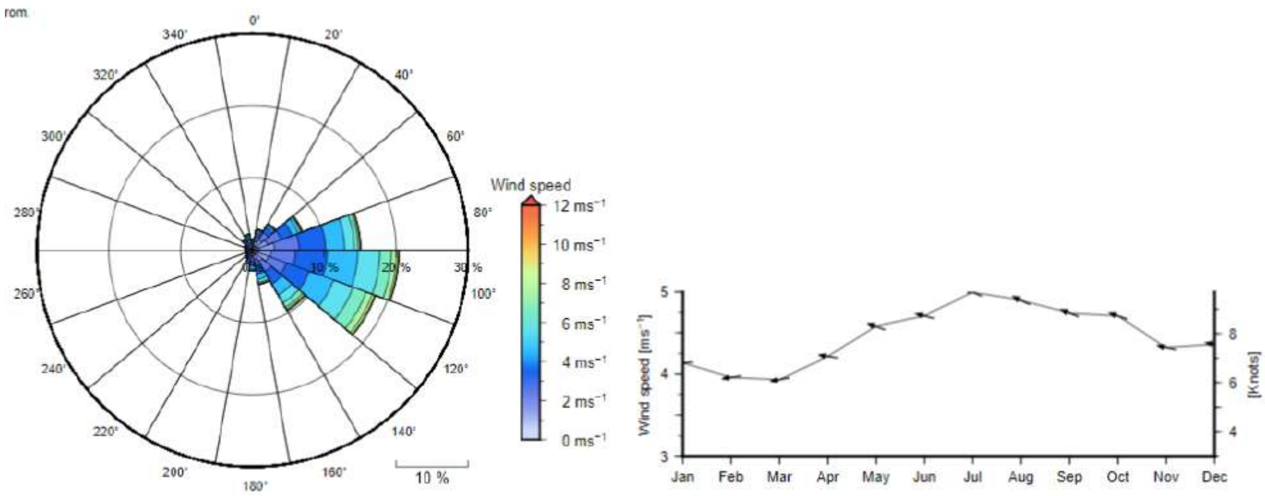

Figure 7: Annual Wind Rose and Monthly Mean Wind Speed for Suva (WACOP, 2015)

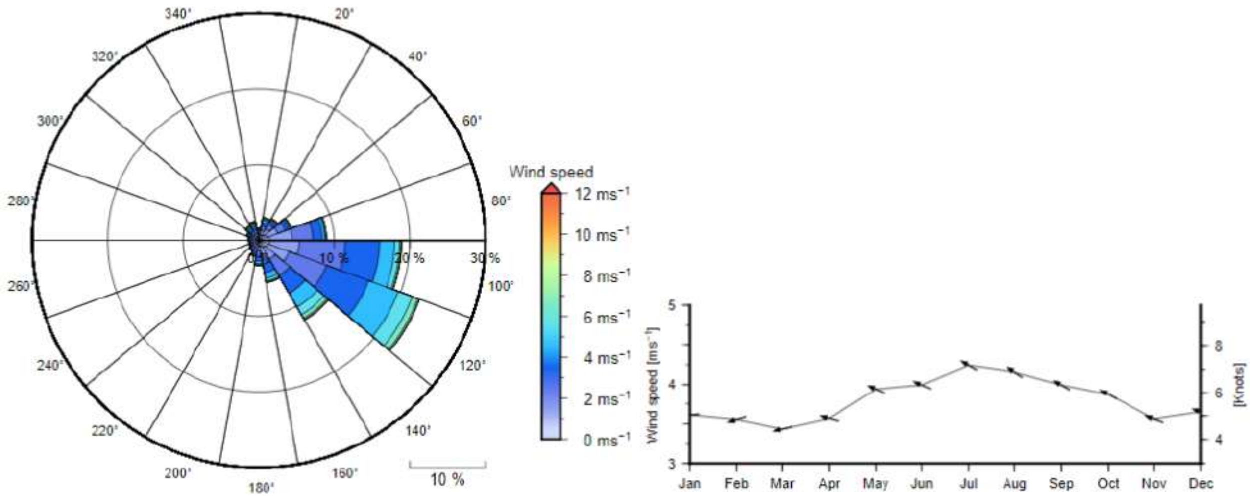

Figure 8: Annual Wind Rose and Monthly Mean Wind Speed for Denarau Marina which is approximately 9km from Viseisei, Lomolomo, Sabeto (WACOP, 2015)

5.1.8 Waves

Although all the Priority 1 bridge sites are located on Viti Levu's coastal ring road, most are positioned several hundred metres upstream from open water and are not exposed to large waves, as indicated in Table 4.2. The exceptions are Lami Bridge and Medraukutu Bridge which are located on the northern shores of Suva Harbour (Figure 9). An initial assessment is shown in Table 5.3.

Table 5.3 Site Specific Wave Exposure

Bridge ID	Name	Description
2905	Medraukutu Bridge	Medraukutu bridge is unlikely to be impacted by large swell waves due to its sheltered location behind reef outcrops and intertidal flats within upper Draunibota Bay (Figure 9). However, wave conditions assessed at Lami bridge are to be considered at Medraukutu bridge. The WACOP site report for Lami (Bosserelle et al., 2015) is closest reporting location to Medraukutu. For the 2-3 hours around high tide, the bridge is potentially exposed to depth limited swell waves entering the harbour and wind waves generated over the 3-4km of fetch from the SSW/SSE within Suva Harbour. These waves are unlikely to be

Bridge ID	Name	Description
		critical for bridge design relative to the design criteria for flood flows but should be considered for scour protection design.
2904	Lami Bridge	Lami Bridge is located directly in line with the navigable entrance to Suva Harbour (Figure 9). This channel allows larger ocean swells to enter the harbour before diffracting/refracting within the sheltered waters. Waves are only able to reach the bridge for the 2-3 hours around high tide, and any waves will become depth limited by shallow reefs within 300-800 m of the bridge site. The WACOP site report (Bosserelle et al., 2015) indicates the mean wave height is 0.29 m from the 190 degrees south and that large waves (> 0.42 m) occur 10% of the time (37 days in a year). In the 34-year wave hindcast 11 wave events exceeded 1m and the 100-year return wind wave height is 2.21m offshore from Lami.
1602	Navutu Bridge	Unlikely to be impacted by waves.
1104	Vunitogoloa Bridge	Unlikely to be impacted by waves.
1415	Visesei Bridge	Unlikely to be impacted by waves.
1107	Vitawa Bridge	Unlikely to be impacted by waves.
1616	Navola Bridge	Some wave propagation may be possible up the river channel, but likely to be minor. The western approach road appears to be near the coastline.
1405	Matawalu Bridge	Unlikely to be impacted by waves.
1419	Sabeto Bridge	Unlikely to be impacted by waves.
1416	Lomolomo Bridge	Unlikely to be impacted by waves.

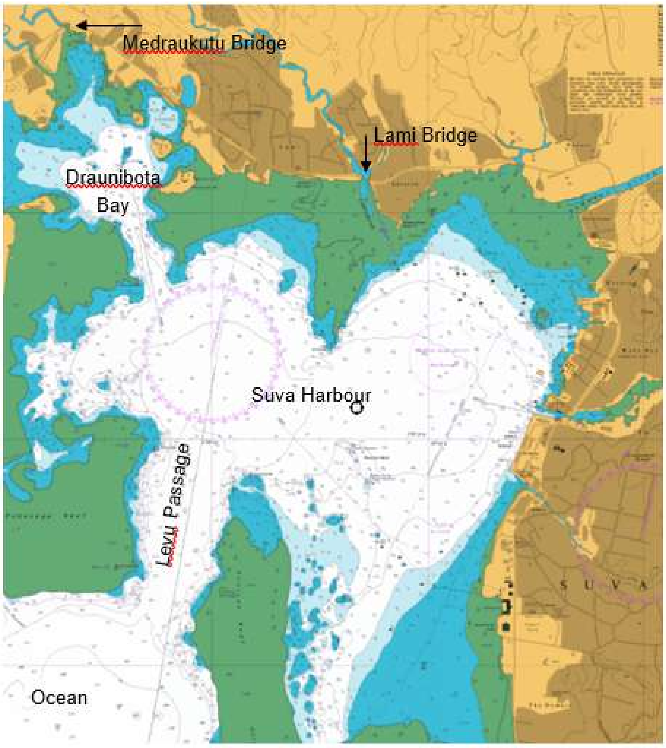

Figure 9: Wave Exposed Priority 1 Bridge Sites. Medrakutu and Lami Bridge on the Northern Shores of Suva Harbour

5.1.9 River Flows

The catchment area and present-day flow at the Priority 1 bridges was estimated. The flood event flows applied to the existing bridges exclude the climate change rainfall increase. For more details, refer to the P1 Hydrology and Flood Modelling Report (Appendix B). Table 5.4 provides a summary of Priority 1 catchment area and flow, excluding climate change.

Table 5.4: Estimates of Catchment Area and Flow

Bridge ID	Name	Catchment Area (km^2)	Peak Flow (m^3/s)				
			10-year [1]	25-year	100-year	500-year	1000-year
2905	Medraukutu	5.52	-	134	171	-	233
2904	Lami	20.75	-	539	687	-	933
1602	Navutu	3.80	-	61	78	-	106
1104	Vunitogoloa	8.91	124	159	209	268	293
1415	Visesei	57.85	-	371	493	-	698
1107	Vitawa	3.67	66	84	111	142	155
1616	Navola	4.35	-	59	76	-	103
1405	Matawalu	69.65	336	423	554	707	773
1419	Sabeto	88.87	-	495	661	-	938
1416	Lomolomo	3.60	-	102	132	-	182

Notes:

1. Only determined for temporary bridges

5.2 Existing Natural Hazards

Fiji is geographically remote and has high exposure to multiple hazards, including flooding, landslides, coastal erosion, tropical cyclones, coastal flooding, earthquake and tsunami.

5.2.1 Catchment-based flooding

a. Existing bridges

Many of the existing Priority 1 bridges are currently exposed to flood hazards during rainfall events, due to their location within floodplains or at the coast, minimal waterway cross-section area, high debris risk, or low soffit levels.

At the early Concept Stage of this project, hydraulic modelling was carried out using HEC-RAS hydraulic flood modelling software to assess the performance of these existing bridges during flood events. HEC-RAS provides a choice of three equation sets to be used for hydraulic modelling. The Concept Stage 2D models for the Priority 1 existing bridges were run using the Diffusion Wave equation set. The Diffusion Wave equation set was used because it results in more stable models with a quicker model run time when compared to the other equation sets. This less intensive equation set was in keeping with the inherent uncertainty of the other model inputs, such as the limited survey and rainfall information.

In July 2023, the external reviewer (SMEC) suggested that flood models should use the Shallow Water Equations (SWE) equation set. The SWE equation set results in better definition of water levels and velocities through abrupt contractions or expansions, bridges and other hydraulic structures. As requested, the hydraulic models were rerun for the proposed permanent and temporary bridges using the SWE equation set. The proposed bridge modelling approach was also refined during the latter stages of the project to account for a bug in the software (relating to modelling bridge piers loaded with debris) and refinements to model boundary conditions. However, the existing bridge models were not updated and rerun using the SWE equation set, given the focus on progressing the design of the permanent bridges and the constraints of the project programme.

As the Diffusion Wave equations and Shallow Water Equation sets, as well as the other changes to modelling approach, result in differing flood levels, the existing bridge hydraulic model results (Diffusion Wave) should not be compared with the permanent bridge hydraulic model results (SWE). Therefore, the existing bridge Diffusion Wave model results are not reported in this Detailed Design stage CRVA report to avoid confusion.

Regardless, the community consultation meetings and socio-cultural surveys that were undertaken as part of this project, highlight the existing flood risk at the Priority 1 existing bridges. Table 5.5 summarises the available local information on flood risk at the Priority 1 existing bridges, obtained from the community consultation (Beca International Consultants Limited, 2021). Note, the locals may have not experienced the 100-year ARI design flood event.

Table 5.5: Summary of Flood Risk Community Consultation Notes for the Existing Priority 1 Bridges

Bridge ID	Bridge Name	Existing Soffit Level (m)	Summary of existing flood risk from community consultation (Beca International Consultants Limited, 2021).	Reported levels compared to existing bridge
2905	Medraukutu	2.1	From socio-cultural survey, opinion varies on flood depth at Medraukutu bridge: halfway up the existing bridge (13%), 2 meters high (9%), and just under the bridge (4%)	Uncertain
2904	Lami	3.5	At community consultation, it was noted rise in water level at bridge is mainly due to trapped debris at bridge, which causes water to backflow sometimes and flood upstream settlements. One survey respondent noted a one-time occurrence of a Lami bridge overtopping flood, 40 years ago.	Uncertain, possibly above the deck
1602	Navutu	4.8	At community consultation, the Fiji Sugar Corporation attendees noted that they have not received any complaints of issues about flooding at Navutu bridge. They also noted that there is no downstream flood gate, allowing water to flow out easily, and they have not encountered any tidal issues.	Below the soffit
1104	Vunitogoloa	1.9	At community consultation, the community requested for the current bridge to be raised to cater for the water flow under the bridge, as the current bridge is too low. They said that debris gets trapped under the	Above the deck

Bridge ID	Bridge Name	Existing Soffit Level (m)	Summary of existing flood risk from community consultation (Beca International Consultants Limited, 2021).	Reported levels compared to existing bridge
			current low bridge and floods the adjacent land. In survey, community leader noted a significant flood event in 2013, where floodwaters went over the bridge. Half of the village was flooded, and evacuation was recommended by the Disaster Management Team. Another survey respondent noted another flood event that occurred in 2009, where the bridge was also overtopped.	
1415	Viseisei	1.5	Community consultation raised that the existing bridge and surrounding land flood during a few hours of rainfall and in extreme events. The villagers requested for the FSC tramline bridge downstream to be removed, as they believe it is the main cause of flooding in the area. They indicated that debris and large trees get stuck on the existing bridge, and water levels can rise quickly. Vuda Pork, near the bridge, has seen water levels almost reach the roof. This is evidenced by marks on a wall showing flood levels.	Above the deck
1107	Vitawa	2.6	At community consultation, villagers raised that the existing bridge floods due to debris blocking the bridge, and floodwaters spill onto surrounding land. Flooding occurs during severe rain or cyclone periods. Flooding was noted as being a significant issue at this site. 76% of survey respondents noted that flooding reached over the bridge level.	Above the deck
1616	Navola	2.8	At community consultation, the Village Chief noted the obstruction of flow by large trees/debris stuck at the bridge, causing flood levels upstream to rise. It was also noted that the river floods during continuous rainfall, which often aligns with high tide occurrences. During the last flood,	Uncertain

Bridge ID	Bridge Name	Existing Soffit Level (m)	Summary of existing flood risk from community consultation (Beca International Consultants Limited, 2021).	Reported levels compared to existing bridge
			the water level rose to knee-high when measured inside one of the homes situated near the river. Survey responses gave varying opinions on the height of floodwaters at the existing bridge.	
1405	Matawalu	4.2	At consultation, a village member mentioned that the old tramline bridge was causing flooding in the village. They also mentioned that whenever there is heavy rain, debris often gets caught in the bridge, causing flooding. The community suggested to raise the bridge, so that water can flow freely. The community members noted that whenever there is continuous heavy rain, the village floods to knee height. Survey respondents noted that in flood events, the flooding went part way up the existing bridge, and over the tramline bridge.	Above the soffit
1419	Sabeto	4.0	At community consultation, locals said that debris get stuck at the bridge whenever it floods, and they feel that they are not safe whilst crossing the river during this time. The villagers hold the belief that during the next occurrence of heavy rain or cyclone, the Sabeto bridge is at high risk of being destroyed by large debris flowing downstream. Consequently, they emphasize the urgent need for the bridge to be replaced as quickly as possible to mitigate this potential threat. The community members confirmed that floodwaters occasionally surpass the bridge. All who noted flooding issues in the survey agreed that flooding reached overtop the bridge.	Above the deck
1416	Lomolomo	1.0	In consultation, the local headman voiced his concern regarding frequent flooding at Lomolomo Bridge, particularly during extended periods of heavy rainfall and high tide events. Community members stated that the existing bridge has been	Above the deck

Bridge ID	Bridge Name	Existing Soffit Level (m)	Summary of existing flood risk from community consultation (Beca International Consultants Limited, 2021).	Reported levels compared to existing bridge
			responsible for causing floods in their village on multiple occasions. The majority of survey respondents stated that the flooding reaches over the existing bridge (60%).	

b. Temporary bridges

As shown in Table 3.2, the proposed temporary bridges are assessed under different design criteria and do not consider the effects of climate change. The following summarises the scenarios considered for the proposed temporary bridges:

- Setting soffit level (maximum water level):
  - SLS1 Case 1: 25-year flow, 10-year sea level, or
  - SLS1 Case 2: 10-year flow, 25-year sea level.
  - ULS: Case 1: 500-year flow, 100-year sea level, or
  - ULS: Case 2: 100-year flow, 500-year sea level.
- Erosion protection (maximum velocity over banks, water depth):
  - SLS1 Normal depth: 25-year flow, no tide.
- Hydraulic loading (maximum velocity on piers and superstructure):
  - ULS: Case 1: 500-year flow, 100-year sea level, or
  - ULS: Case 2: 100-year flow, 500-year sea level.

Table 5.6 summarises the maximum water level and velocity at the temporary bridges.

Table 5.6: Estimates of Maximum Water Level and Velocity at Temporary Bridges

Bridge ID	Bridge Name	Maximum Water Level (m)		Maximum Velocity Over Banks (m/s)	Water Depth (m)	Maximum Velocity on Superstructure (m/s)	
		SLS1	ULS	SLS1	SLS1	ULS: Piers	ULS: Superstructure
B4	Vunitogoloa Temporary Bridge	3.5	3.9	1.6	3.2	No piers	1.8
B6	Vitawa Temporary culverts	4.0	4.6	-	-	-	-
B8	Matawalu Temporary Bridge	3.3	3.9	1.6	4.8	No piers	2.8

5.2.2 Riverbank Erosion

All the priority 1 bridges pass over waterways therefore, piers located in the waterways and abutments are likely to be exposed to scour and riverbank erosion. Based on aerial images, the riverbanks at each site appear to be stable. However, it is assumed that erosion is currently managed by protection such as rip rap or an appropriately graded slope considering river flows.

5.2.3 Landslides

Rainfall and seismic induced landslides are a significant risk in Fiji due to the country's steep terrain, weathered rock properties, and frequent cyclone, storm, heavy rainfall and seismic events. A recent global landslide susceptibility map shows Fiji as having moderate to very high susceptibility in the interior of each island, based on analysis of slope, forest loss, presence of roads, and seismicity (Government of the Republic of Fiji, 2017). Landslides in Fiji are known to impact road networks and river flows.

Landslide risks are likely to increase with climate change. The heavy precipitation increase observed in most climate models would also increase the probability of landslides (Government of the Republic of Fiji, 2017). Similarly, an increase in the more intense tropical cyclones could lead to increased landslide risk. However, landslide susceptibility also depends on other complex factors, such as land use, deforestation, and slope management, which are difficult to predict.

5.2.4 Coastal Erosion

All the Priority 1 bridge sites are located on Viti Levu's coastal ring road, most positioned several hundred metres upstream from open water. These bridges are not subject to coastal processes (e.g. waves) except tidal water levels and storm surge. Table 5.7 summarises the likely impact of coastal erosion on the Priority 1 bridges.

Table 5.7: Site Specific Coastal Erosion

Bridge ID	Name	Description
2905	Medraukutu Bridge	Medraukutu bridge is unlikely to be impacted by coastal erosion due to its sheltered location behind reef outcrops and intertidal flats within upper Draunibota Bay. Based on aerial imagery, it is located in an area of accretion evidenced by mud flats.
2904	Lami Bridge	Lami Bridge is located directly in line with the navigable entrance to Suva Harbour and can be exposed to waves during high tide. However, due to its location within a low-energy coastal environment, coastal erosion is unlikely.
1602	Navutu Bridge	Unlikely to be impacted by coastal erosion.
1104	Vunitogoloa Bridge	Unlikely to be impacted by coastal erosion.
1415	Visesei Bridge	Unlikely to be impacted by coastal erosion.
1107	Vitawa Bridge	Unlikely to be impacted by coastal erosion.
1616	Navola Bridge	Navola Bridge is unlikely to be impacted by coastal erosion as it is located 100m inland of the coastline. As seen in aerial imagery, the coastline to the east shows evidence of encroaching on Queens Road.
1405	Matawalu Bridge	Unlikely to be impacted by coastal erosion.
1419	Sabeto Bridge	Unlikely to be impacted by coastal erosion.
1416	Lomolomo Bridge	Unlikely to be impacted by coastal erosion.

5.2.5 Tropical Cyclones

Tropical cyclones usually affect Fiji between November and April and occasionally in October. In the 42-year period between the 1969 and 2010 seasons, 117 tropical cyclones developed within or passed through Fiji's Exclusive Economic Zone, an average of 28 per decade. The number of tropical cyclones varies widely from year to year, with none in some seasons but up to six in others (MetOcean, 2022).

In the past 10-year period between the 2012 and 2022 seasons, seven tropical cyclones passed within a radius of approximately 500km of Vitu Levu, that caused noticeable perturbation in the measured winds and atmospheric pressure at weather stations shown in Figure 10.

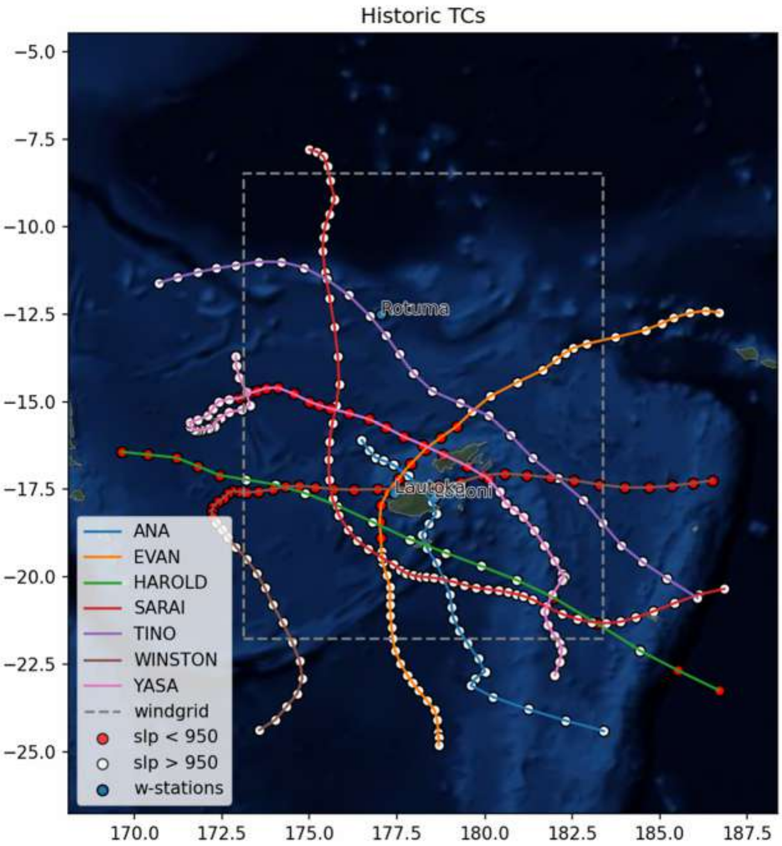

Figure 10: Trimmed tracks of the historical tropical cyclones used for model calibration and validation. Dots along track represent points where the TC central pressure is lower (white) and higher than 950 hPa (in red). Blue dots indicate the location of the weather stations whilst the grey dashed area delimitates the study area. (MetOcean, 2022)

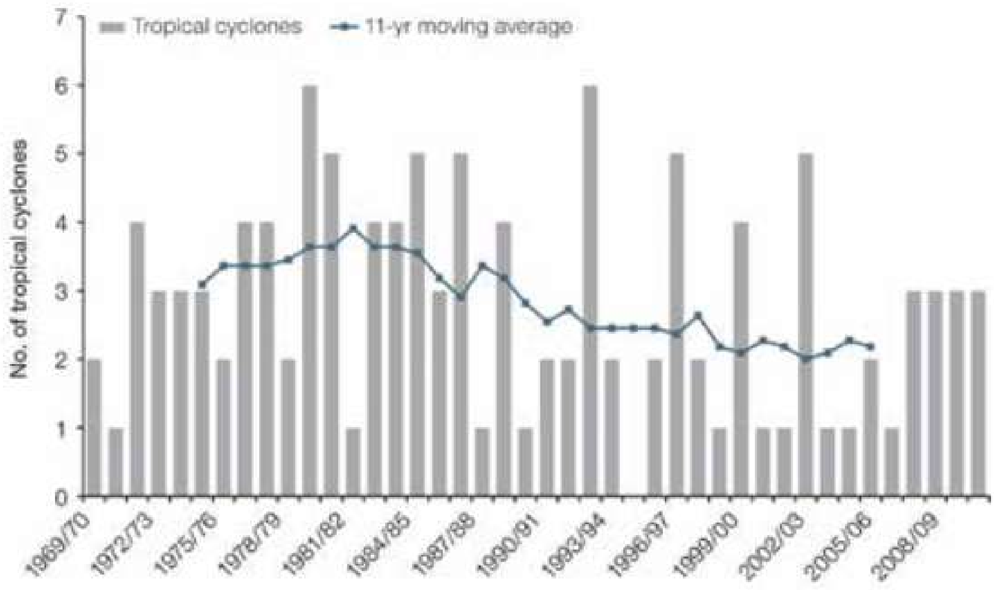

Figure 11: Number of Tropical Cyclones Developing Within and Crossing the Fiji Exclusive Economic Zone Per Season (PACCSAP, 2014)

5.2.6 Coastal Flooding

Analysis of coastal flooding identifies tropical cyclones as the main driver of extreme sea levels in Fiji (Government of the Republic of Fiji, 2017). Flooding in low-lying coastal areas results from the combination of four contributors: mean sea level (plus sea-level rise), astronomical tide, storm surge due to low pressure and cyclone wind action, and wave-induced increases in sea level. Coastal flooding can result from an exceptional intensity of a single process (e.g., storm surge), but more often results from the combination of the four processes.

The effect of storm waves interacting with the local reef topography leads to “wave setup,” which is the sustained increase in water surface elevation at the coast by the ‘piling up’ of water at the shoreline and can be combined with low-frequency infra-gravity waves over the reef flats. Wave setup is particularly important for Fiji because of the presence of steep-shelved coastlines, narrow fringing reefs and narrow reef passages which drain the reef lagoons.

5.2.7 Earthquake

Fiji is within an area of relatively low seismicity, but it is surrounded by the Pacific Ring of Fire. The region aligns with the boundaries of the tectonic plates and is associated with extreme seismic activity, volcanic activity, and tsunamis. Fiji has a 40 percent chance of experiencing moderate to strong ground shaking at least once in the next 50 years (Government of the Republic of Fiji, 2017).

The majority of large earthquakes have been reported along the tectonic boundaries that surround the Fiji Platform. Significant earthquakes have occurred within the platform, such as the 1953 Suva and 1979 Taveuni earthquakes, they all had magnitudes less than Mw7.1, but they were extremely damaging suggesting, that the thin lithosphere of the Fiji region is incapable of storing sufficient stress that results from earthquakes. Studies of the magnitude and frequency of earthquake recurrence intervals suggest that earthquakes of magnitude 7 or greater are expected every 15-21 years and earthquakes of magnitude 6.5 or greater are expected every 2.5-6 years. Earthquake potential is not uniform throughout the Fiji region (Hamburger et al, 1986).

Earthquakes may result in liquefaction of saturated silty/sandy soils around the coastal plain (Varo et al., 2019).

5.2.8 Tsunami

Earthquake generated tsunamis are a major hazard to Fiji. Fiji is subject to regular tsunami warnings as a result of large-magnitude events in the region, events that could potentially result in tsunami run-up and damage. The National Oceanic and Atmospheric Administration (NOAA) and National Centres for Environmental Information (NCEI) tsunami run-up database records only five tsunamis that have caused runup in Fiji. Widespread run-up exceeding 1m in height occurred following the Suva Earthquake in 1953, and four other events with uncertain or insignificant run-up were recorded in 1881, 1884, 1979, 2017 and 2022. The Global Tsunami Model (GTM) estimates that maximum inundation heights on southwest-facing coasts of Fiji could exceed 4 m on average once in a 500-year period (i.e., such an event has a 0.2 percent chance of occurring in any given year) (Government of the Republic of Fiji, 2017). This estimate accounts for regional tsunamis affecting Fiji.

Tonkin & Taylor (2020) analysed Fijis tsunami risk and developed hazard mapping for major urban centres on Viti Levu and Vanua Levu. Tsunami inundation zones were identified using a combination of hydrodynamic models and probabilistic approaches. The predicted inundation resulting from a 10,000-year event exceeded 6m in the north, east and south of the island as shown in Figure 12.

Figure 12: Results from Probabilistic Tsunami Hazard Assessment for Viti Levu Undertaken by Tonkin & Taylor (2020)

The occurrence of geophysical events such as earthquakes and tsunamis are not caused or influenced by climate change. However, the consequences of a tsunami are exacerbated by sea-level rise, which increases the fraction of the population and assets exposed to this hazard.

6 Climate Change Projections for Fiji

Climate change has the potential to exacerbate the climatic and natural hazards that affect Fiji, although projecting these future hazards at a local scale can be challenging in the absence of detailed topographic and bathymetric information.

The information used in this CRVA and DRA is drawn from the two latest iterations of the Intergovernmental Panel on Climate Change (IPCC). The Sixth Assessment Report (AR6, 2021) is primarily available at global and regional scales but requires supplementary information from the Fifth Assessment Report (AR5, 2013) as these results have been downscaled for more local uses across the Pacific. Climate change projections from AR6 have been adopted for this CRVA and DRA and where information is insufficient AR5 projections along with supplementary information has been utilised.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC, 2013) provided guidance on climate change projections for different representative concentration pathways (RCPs). The pathways describe different climate futures, all considered possible depending on the volume of greenhouse gases emitted in the years to come. The four different RCP scenarios are as follows:

- RCP2.6 — the most ambitious mitigation scenario. CO_2 emissions peak around 2020 and rapidly decline thereafter.
- RCP4.5 —CO_2 emissions peak around 2040 and CO_2 concentration reaches 540 ppm by 2100.
- RCP6.0 — lower emissions, achieved by the application of some mitigation strategies and technologies. CO_2 reaches 660 ppm by 2100 and total radiative forcing stabilising shortly after 2100.
- RCP8.5 — a future with little curbing of emissions, with CO_2 concentrations continuing to rise rapidly reaching 940 ppm by 2100.

The latest IPCC 6th Assessment Report (AR6) (2021) has introduced a set of five new illustrative emissions scenarios and projections that differ from prior assessments, AR6 has used a new set of scenarios derived from Shared Socioeconomic Pathways (SSPs). The pathways describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the years to come. The five different SSP scenarios are as follows:

- SSP1-1.9: the most optimistic scenario where global CO_2 emissions are cut to net zero around 2050.
- SSP1-2.6: global CO_2 emissions are cut severely reaching net zero after 2050.
- SSP2-4.5: CO_2 emissions are maintained until 2050 and begin to decline but do not reach net zero by 2100.
- SSP3-7.0: CO_2 emissions continue to rise to double by 2100.
- SSP5-8.5: Current CO_2 emissions double by 2050.

Future projections of climate change are assessed via the use of mathematical models that represent the Earth's climate system. The models are complex, and all have inherent limitations representing climate processes. While there is no standard model, a group of models that are currently the "best" are brought together and compared via the Coupled Model Intercomparison Project (CMIP), with the latest complete version being CMIP6 which is the foundation dataset for AR6.

Many climate projections use the set of CMIP5 global climate models. The new models show improvements in simulating the climate of the western Pacific. Many issues remain and the projections still show a wide range of possible changes (CSIRO and SPREP, 2021).

For Fiji, two different changes in the regional climate for each of the pathways are plausibly governed by the movement of SPCZ. If the SPCZ moves north, warmer and drier conditions are possible, but if it moves south, warmer and wetter conditions are expected. For the purposes of this CRVA and DRA, the more onerous condition to design will be taken forward for assessment.

Climate change has the potential to exacerbate the hazards that affect Fiji, although projecting these future hazards is challenging. Difficulties in predicting how hazards will change in the future arise from two key factors. First, there are deep uncertainties concerning the speed and sometimes direction of climate changes, especially at local scales. Different climate models project very different changes in rainfall and storm surge, leading to uncertainty in overall projections. Second, the models used to project climate data use spatial resolutions that are too coarse to fully represent the future climate of small islands. Many of Fiji's islands are smaller than the grid squares of the global circulation models (GCMs) that underpin the climate projections (grid squares are 200–600km^2, depending on the model) (Fiji, 2017).

Only SSP1-2.6 and SSP5-8.5 are projected to 2300, but there is deep uncertainty about the future of climate change trajectory past 2100. Simulations that extend beyond 2100 for the other scenarios are too few for robust results.

6.1 Sea-level Rise

The latest projections from IPCC (2021) suggest that the global mean sea level will continue to rise throughout the 21st century. Sea level rise (SLR) projections applicable throughout Fiji are presented in Figure 13 and Figure 14. The projections have been adjusted for the upper bound of the most likely long-term vertical land movement with a constant subsidence rate of -1.0mm/year, as discussed in section 5.1.5.

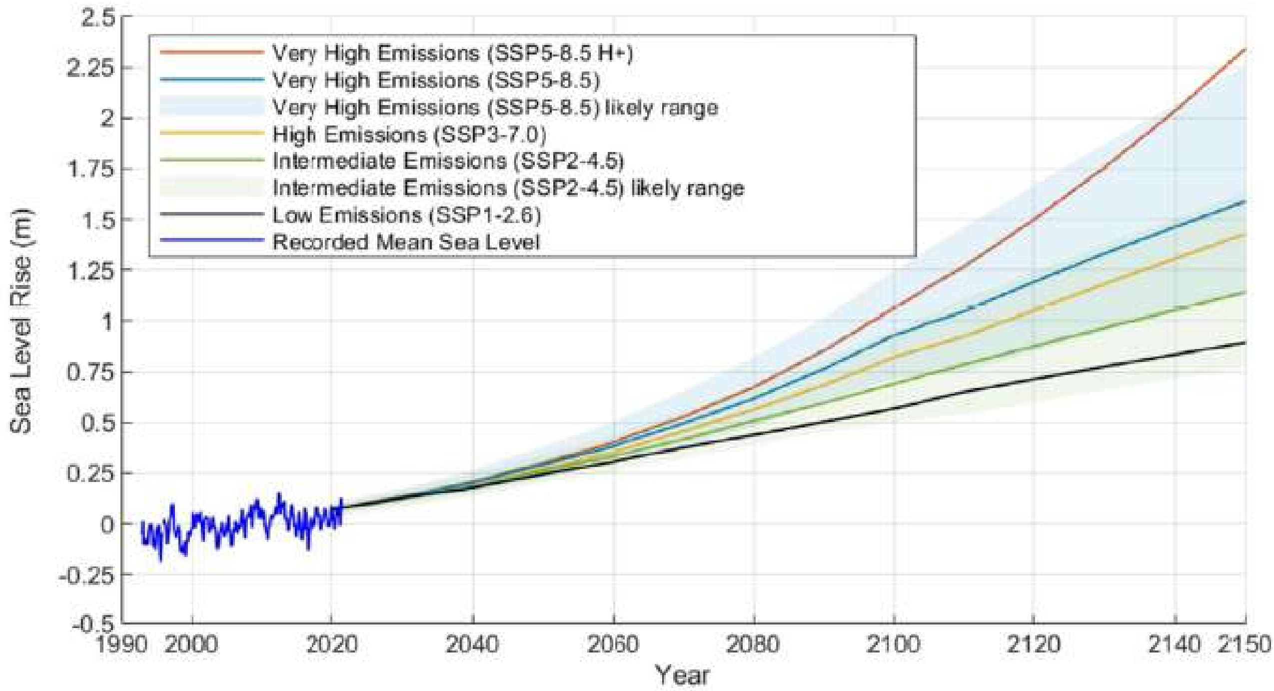

Figure 13: Projected Mean Sea-level Rise in Fiji under Various SSPs. Source: PRIF (2022) and IPCC AR6 WG1 (2021, Figure 9.27).

Year	Low SSP1-2.6	Intermediate SSP2-4.5	High SSP3-7.0	Very High SSP5-8.5	Very High – Low SSP5-8.5 H+
1995-2014	0.00	0.00	0.00	0.00	0.00
2020	0.07 (0.04–0.10)	0.07 (0.03–0.11)	0.07 (0.04–0.09)	0.07 (0.04–0.10)	0.07 (0.04–0.11)
2030	0.13 (0.09–0.17)	0.13 (0.08–0.17)	0.12 (0.09–0.16)	0.13 (0.10–0.17)	0.14 (0.10–0.20)
2040	0.18 (0.13–0.24)	0.18 (0.13–0.25)	0.19 (0.14–0.25)	0.20 (0.15–0.27)	0.21 (0.15–0.33)
2050	0.25 (0.18–0.33)	0.26 (0.20–0.34)	0.27 (0.20–0.36)	0.29 (0.22–0.38)	0.30 (0.22–0.49)
2060	0.31 (0.23–0.41)	0.33 (0.26–0.44)	0.35 (0.28–0.46)	0.38 (0.30–0.50)	0.40 (0.30–0.68)
2070	0.38 (0.29–0.50)	0.42 (0.32–0.56)	0.46 (0.36–0.59)	0.49 (0.39–0.65)	0.53 (0.39–0.93)
2080	0.44 (0.34–0.59)	0.51 (0.39–0.68)	0.56 (0.44–0.74)	0.62 (0.48–0.82)	0.67 (0.48–1.21)
2090	0.50 (0.38–0.69)	0.60 (0.45–0.81)	0.68 (0.54–0.91)	0.76 (0.60–1.02)	0.85 (0.60–1.54)
2100	0.57 (0.41–0.79)	0.69 (0.50–0.96)	0.82 (0.62–1.11)	0.93 (0.72–1.25)	1.07 (0.72–1.89)
2110	0.65 (0.45–0.92)	0.78 (0.54–1.11)	0.92 (0.65–1.28)	1.05 (0.75–1.46)	1.27 (0.75–2.23)
2120	0.71 (0.49–1.02)	0.88 (0.60–1.24)	1.05 (0.73–1.46)	1.19 (0.85–1.67)	1.50 (0.85–2.56)
2130	0.78 (0.53–1.11)	0.97 (0.66–1.38)	1.18 (0.82–1.65)	1.33 (0.95–1.87)	1.76 (0.95–3.34)
2140	0.83 (0.56–1.20)	1.05 (0.72–1.51)	1.31 (0.91–1.83)	1.46 (1.04–2.07)	2.04 (1.04–4.42)
2150	0.89 (0.60–1.30)	1.14 (0.77–1.64)	1.43 (0.99–2.01)	1.59 (1.13–2.26)	2.34 (1.13–5.60)

Figure 14: Extract from PRIF (2022) Showing the Decadal Increments for Projections of Sea Level Rise in Meters for Fiji Relative to the 1995-2014 Mean Sea Level

Median values are often referenced for a given period and pathway but as seen in Figure 14, the median magnitudes of projections for low emissions (SSP1-2.6) to very high emissions (SSP5-8.5) are within the likely range of the intermediate emissions (SSP2-4.5) scenario.

The median estimates of sea level rise from AR6 SSP scenarios, referenced to the 1995-2014 mean sea level baseline period and adjusted for long-term subsidence trends of Fiji, are presented in Table 6.1 below for 50-year and 100-year bridge design lives/periods.

As detailed in RFI 105 (Beca, 2022) on 25 February 2022, FRA wishes to maintain consistency with the magnitudes of sea level rise presented in the FRA Design Guide. This will depart from Austroads Design Guide Supplement Part 1 to 8 (dated March 2019) with revised magnitudes of sea level rise for engineering design.

The magnitude of sea level rise for CRVA and DRA shall be 0.73m (SSP1-2.6) and 1.09m (SSP3-7.0), respectively referenced to the 1995-2014 mean sea level baseline.

Table 6.1: Sea Level Rise Projection for 2073 and 2123 (IPCC AR6, 2021)

Year	Low SSP1-2.6	Medium SSP2-4.5	Medium-High SSP3-7.0	Very High SSP5-8.5	Extreme SSP5-8.5H+
2073 (i.e. until the end of the 50 years design life)	0.40	0.45	**0.49**	0.53	0.57
2123 (i.e. until the end of the 100 years design life)	**0.73**	0.91	**1.09**	1.23	1.58

We note that SLR will continue beyond 100 years regardless of the future climate pathway with the latest IPCC projections showing SLR continuing to 2300 and beyond due to 'locked-in' sea level rise as a result of historic emissions and the lagged thermal expansion of the oceans.

6.1.1 Coastal Flooding

As relative sea levels increase, the potential for coastal flooding increases. The increases in high-tide and storm-event water elevations will result in an increased likelihood of large waves overwashing the beach face and impacting near-coast assets, land, and infrastructure, and will exacerbate catchment flooding during high rainfall events. Table 6.2 shows the tide level including SLR for 2123.

The potential increase in extreme sea levels from the effects of sea level rise is widely recognised as a critical risk for coastal infrastructure. Extreme sea levels include the contributions from mean sea level, storm surges and tides. Even a small increase in mean sea level can significantly change the frequency and intensity of all coastal hazards (IPCC, 2019).

Table 6.2: Locally Derived Tidal Levels Adjusted for Climate Change, 2123 Relative to Local MSL Datum

Bridge ID	Name	MSL		MHWS		MLWS	
		SSP1-2.6	SSP3-7.0	SSP1-2.6	SSP3-7.0	SSP1-2.6	SSP3-7.0
2905	Medraukutu Bridge	1.29	1.65	1.99	2.35	0.59	0.95
2904	Lami Bridge	0.96	1.32	1.66	2.02	0.26	0.62
1602	Navutu Bridge	1.57	1.93	2.42	2.78	0.82	1.18
1104	Vunitogoloa Bridge	1.56	1.92	2.31	2.67	0.81	1.17
1415	Visesei Bridge	0.99	1.35	1.72	2.08	0.22	0.58
1107	Vitawa Bridge	2.44	2.80	3.19	3.55	1.69	2.05
1616	Navola Bridge	1.83	2.19	2.39	2.75	1.29	1.65
1405	Matawalu Bridge	0.94	1.30	1.79	2.15	0.19	0.55
1419	Sabeto Bridge	0.77	1.13	1.50	1.86	0.00	0.36
1416	Lomolomo Bridge	1.02	1.38	1.75	2.11	0.25	0.61

6.1.2 Coastal Erosion

IPCC AR6 projections indicate that shoreline retreat is likely to occur over most of the small islands in the Pacific throughout the 21st century as a result of sea-level rise and climate change. Average shoreline retreat rates between 1 and 2 m/year are estimated for the islands in the equatorial Pacific based on satellite observations from 1984–2016 (IPCC AR6 WG1 Chapter 12, 2021).

However, there is ongoing research into the ability of the coral reef systems to ‘keep up’ with the sea level rise through the increased production of corals sand material which may be washed onto the beach faces and resupply the beaches. The local anthropogenic factors (e.g. seawalls, reclamation, sediment extraction) will also affect the local erosion rates and vulnerability of beaches (IPCC 2021).

6.1.3 Coastal Hazards

Sea level rise exacerbates all coastal hazards such as tsunamis, storm surge, waves, groundwater, lagoon levels and river tailwater level.

6.2 Air Temperature

AR6 provides a minimum and maximum temperature changes for different Pacific Country zones. Consistent with global trends, further warming is expected over Fiji. Projections for all future SSP scenarios indicate increases in annual and seasonal averages and maximum daily air temperature. Table 6.3 shows the projected change in mean annual air temperature for Fiji, as per the CMIP6 model ensemble.

Table 6.3: Mean Annual Temperature change Relative to the 1995-2014 Baseline for Fiji of 25.8°C. SSP Projections Based on IPCC (2021) Sourced from AR6 Interactive Atlas

Year	Low SSP1-2.6	Medium SSP2-4.5	Medium-High SSP3-7.0	Very High SSP5-8.5
Baseline 1995-2014	0.0	0.0	0.0	0.0
Near Term (2021-2040)	0.5	0.5	0.5	0.5
Medium Term (2041-2060)	0.8	0.9	1	1.2
Long Term (2081-2100)	0.8	1.5	2.2	2.8
2123 (i.e. until the end of the 100 years design life)[1]	**0.8**	**1.9**	**2.8**	**3.7**

Notes:

1. Values extrapolated using near term to long term relative temperature change to year 2123.

6.3 Rainfall

There is little agreement on the magnitude of expected change to annual average rainfall, with considerable differences among the outputs of the different climate models. Table 6.4 summarises the projected change in annual rainfall relative to the 1995-2014 baseline.

Table 6.4: Mean Annual Rainfall Change Relative to the 1995-2014 Baseline for Fiji. SSP Projections Based on IPCC (2021) Sourced from AR6 Interactive Atlas

Year	SSP1-2.6 (%)	SSP2-4.5 (%)	SSP3-7.0 (%)	SSP5-8.5 (%)
1995-2014	0	0	0	0
Near Term (2021-2040)	0.6	0.9	0.6	1.2
Medium Term (2041-2060)	0.4	1.6	1.5	1.1
Long Term (2081-2100)	-0.2	0.6	1.3	1.8
2123 (i.e. until the end of the 100 years design life)[1]	**-0.5**	**0.6**	**1.7**	**2.0**

Notes:

1. Values extrapolated using near term to long term relative temperature change to year 2123.

The uncertainty associated with the projections summarised in Table 6.4 is high. Climate models do not show agreement; some models project an increase in precipitation while others project a decrease. This disagreement on future precipitation presents a significant obstacle in terms of planning for climate change adaptation. However, extreme daily rainfall events in Fiji are expected to increase in both frequency and intensity. In agreement with global trends, it is very likely that heavy precipitation events will intensify and become more frequent. Shown in Table 6.5, extreme daily precipitation events are projected to intensify by the end of the century from a range of 4.6 to 19.4% for SSP1-2.6 and SSP5-8.5, respectively.

Table 6.5 Maximum 1-day Precipitation Change Relative to the 1995-2014 Baseline for Fiji. SSP Projections Based on IPCC (2021) Sourced from AR6 Interactive Atlas

Year	SSP1-2.6 (%)	SSP2-4.5 (%)	SSP3-7.0 (%)	SSP5-8.5 (%)
1995-2014	0	0	0	0
Near Term (2021-2040)	2.6	2.9	3	3.4
Medium Term (2041-2060)	4.5	5.5	6.3	7.6
Long Term (2081-2100)	4.6	8.6	14.6	19.4

Year	SSP1-2.6 (%)	SSP2-4.5 (%)	SSP3-7.0 (%)	SSP5-8.5 (%)
2123 (i.e. until the end of the 100 years design life)1	4.7	10.9	19.0	25.4

Notes:

1. Values extrapolated using near term to long term relative temperature change to year 2123.

The projected impacts of climate change on extreme rainfall intensity have been approximated using the Clausius-Clapeyron rate. It has been demonstrated that for tropical regions such as Fiji, the impacts of climate change could increase extreme sub-daily rainfall intensity by a rate of 1.5-3 times greater than the increases expected based on the Clasius-Clapeyron rate used in IPCC (2021). This is referred to as Super-Clausius-Clapeyron (Super-CC) scaling. ADB (2021) provides guidance to determine the initial scaling factor based on Guerreiro et al. (2018). To apply the Super-CC scaling to daily rainfall extremes, use the percentage increase determined by the initial scaling factor is multiplied by 1.5 and then rounded up to the nearest 5% for daily rainfall intensities. For short-duration rainfall extremes such as hourly or sub-hourly, a greater factor is applied, up to 3 times Clasius-Clapeyron.

Table 6.6 provides a percentage increase in extreme daily precipitation events using Super-CC scaling on World Bank Climate Change Knowledge Portal (n.d.).

Table 6.6: Maximum 1-day Precipitation Change Relative to 1995-2014 Baseline for Fiji using Super-CC Scaling. SSP Projects Extracted from World Bank Climate Change Knowledge Portal. (n.d.)

Year	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
1995-2014 Temperature change (C°)	0 (24.91)	0 (24.91)	0 (24.91)	0 (24.91)
1995-2014 Rainfall Intensity	**0%**	**0%**	**0%**	**0%**
2100 Temperature change (C°)	0.57 (25.48)	1.42 (26.33)	2.41 (27.32)	2.93 (27.84)
2100 Rainfall Intensity	**10%**	**15%**	**25%**	**30%**
2123 Temperature change[1] (C°)	0.82 (25.73)	1.88 (26.79)	2.98 (27.32)	3.77 (28.68)
2123 Rainfall intensity	**10%**	**20%**	**30%**	**40%**

Notes:

1. Values based on extrapolated values to 2123 should be taken with caution.

The percentage increase in rainfall intensity for CRVA and DRA shall be 10% (SSP1-2.6) and 40% (SSP5-8.5), respectively referenced to the 1995-2014 rainfall intensity, which is consistent with the percentage presented in the FRA Design Guide.

6.3.1 River Flows

The catchment area and flow at the proposed permanent Priority 1 bridges was estimated using standard hydrological modelling methods. The influence of climate change was assessed in accordance with the Design Criteria Bridges Priority 1 (Beca, 2022) as agreed with FRA using the 10% or 40% rainfall depth increase, based on SSP1-2.6 and SSP1-8.5. For more details, refer to the P1 Hydrology and Flood Modelling Report (Beca, 2023 - refer to appendix B). Table 6.7 provides a summary of catchment area and flow for Priority 1 bridges, inclusive of climate change adjustments.

Table 6.7: Estimates of Catchment Area and Flow

Bridge ID	Name	Peak Flow (m^3/s)					
		25-year +10% CC	25-year +40% CC	100-year +10% CC	100-year +40% CC	1000-year +10% CC	1000-year +40% CC
2905	Medraukutu	150	196	191	248	258	334
2904	Lami	601	787	764	993	1033	1333
1602	Navutu	68	88	86	111	117	150
1104	Vunitogoloa	177	231	232	301	324	417
1415	Visesei	417	555	552	727	777	1012
1107	Vitawa	94	122	123	159	171	220
1616	Navola	67	90	85	113	115	151
1405	Matawalu	475	631	619	814	860	1120
1419	Sabeto	557	745	740	977	1045	1365
1416	Lomolomo	114	147	146	189	201	258

Notes:

1. CC refers to climate change. Refer to section 6.3 for details.

6.3.2 Catchment-based Flooding

Site specific catchment-based flood modelling was performed using Hydrologic Engineering Centre's River Analysis System (HEC-RAS). Several model scenarios were performed which are used as inputs into this CRVA and DRA to determine appropriate bridge design considerations. For more details, refer to the P1 Hydrology and Flood Modelling Report (Beca, 2023-refer to appendix B). The following summarises the scenarios considered for the permanent bridge design:

- Setting soffit level (maximum water level):
  - SLS1 Case 1: 100-year flow, 20-year sea level, or
  - SLS1 Case 2: 25-year flow, 100-year sea level.
  - ULS: Case 1: 1000-year flow, 100-year sea level, or
  - ULS: Case 2: 100-year flow, 1000-year sea level.
- Erosion protection (maximum velocity over banks, water depth):
  - SLS1: Normal depth: 100-year flow, no tide.
- Hydraulic loading (maximum velocity on piers and superstructure):
  - ULS: Case 1: 1000-year flow, 100-year sea level, or
  - ULS: Case 2: 100-year flow, 1000-year sea level, or
  - ULS: Normal depth: 1000-year flow, no tide.

Table 6.8 summarises the permanent bridge hydraulic model results, used for setting the bridge soffit level, erosion protection, and hydraulic loading. The model runs these results are from all use a 10% increase in rainfall depth and a 0.73m increase in sea level, to account for climate change.

Table 6.8 Estimates of Maximum Water Level and Flow Velocity at Permanent Bridges

Bridge ID	Bridge Name	Maximum Water Level (m)		Maximum Bank Velocity (m/s)	Water Depth (m)	Maximum Flow Velocity on Structure (m/s)	
		SLS2 10% CC	ULS 10% CC	SLS2 (no tide) 10% CC	SLS2 (no tide) 10% CC	ULS 10% CC: Piers	ULS 10% CC: Super-structure
2905	Medraukutu	2.5	3.0	1.8	3.0	1.6	2.0
2904	Lami	2.8	3.2	4.8	5.8	4.3	4.3
1602	Navutu	4.0	5.0	2.8	4.0	1.5	1.6
1104	Vunitogoloa	4.0	4.8	1.7	4.1	1.6	1.7
1415	Visesei	3.1	4.2	1.8	5.8	2.5	2.8
1107	Vitawa	4.7	5.8	3.4	4.0	0.7	1.4
1616	Navola	3.6	3.9	1.1	3.8	1.0	1.8
1405	Matawalu	4.3	4.7	3.2	6.1	3.5	2.7
1419	Sabeto	3.8	4.2	4.3	6.6	3.9	4.3
1416	Lomolomo	3.2	4.1	2.1	3.9	1.0	0.7

Notes:

CC refers to climate change. Refer to section 6.3 for details.

6.4 Drought

As discussed in Section 6.3, there is uncertainty whether annual precipitation will increase or decrease with climate change. However, projections show that Fiji will experience an intensified seasonal cycle, such as a decrease in rainfall in the dry season and an increase in rainfall in the wet season (Rhee & Yang, 2018).

6.5 Wind Speed

AR6 provides surface wind speed change for different Pacific Country zones. Consistent with global trends, increased wind speeds are expected over Fiji. Projections for all future SSP scenarios indicate increases in wind speed. Table 6.9 gives the projected change in mean annual air temperature for Fiji as per the CMIP6 model ensemble.

Table 6.9: Surface Wind Change Relative to the 1995-2014 Baseline for Fiji. SSP Projections Based on IPCC (2021) Sourced from AR6 Interactive Atlas

Year	SSP1-2.6 (%)	SSP2-4.5 (%)	SSP3-7.0 (%)	SSP5-8.5 (%)
1995-2014	0	0	0	0
Near Term (2021-2040)	0.3	0.6	0.6	0.4
Medium Term (2041-2060)	0.8	0.8	0.4	0.8
Long Term (2081-2100)	0.9	1.3	1.3	2.0
2123 (i.e. until the end of the 100 years design life)1	1.0	1.6	1.5	2.6

Notes:

Year	SSP1-2.6 (%)	SSP2-4.5 (%)	SSP3-7.0 (%)	SSP5-8.5 (%)

1. Values extrapolated using near term to long term relative temperature change to year 2123.

6.6 Tropical Cyclones

A recent study by Knutson et al. (2020) assesses the impact of a 2°C global warming on TC activity around the world. Below are some key messages from that study relevant to the broader southwest Pacific region; care must be exercised when interpreting these results for any local region in the Pacific, such as Fiji.

- High confidence that TC frequency will decrease over the coming century.
- Low confidence in the changes in the frequency of category 4-5 TCs.
- High confidence that sea level rise will increase TC-related storm surge events.
- Medium to high confidence in an increase in TC rainfall rates.
- Medium to high confidence in the increase in average TC intensity.

Globally tropical cyclone intensity is expected to increase by 1% to 10% with a median increase of 5%. Intensity within the Southwest Pacific is more uncertain, with projected changes varying from -6% to 12% and a median of 1% (PRIF, 2022). The projected increase in average TC intensity, combined with sea level rise and increased rainfall rates, would increase TC impacts (CSIRO and SPREP, 2021).

McInnes (2014) found that for a sea level rise scenario of 0.31m, the frequency of 100-year storm tide levels increased by a factor of around 1.5 for locations most affected by tropical cyclone storm surges (Nadi, Lautoka) to a factor of 4 or more for locations less affected by tropical cyclone storm surges; these factors being related to the steepness of the return period curves for the two locations.

7 Vulnerability Assessment

7.1 Preliminary Screening

This section presents an initial screening of potential impacts of, and vulnerability to, the identified hazards from climate and disaster hazards for the ten priority 1 bridges.

For each of the hazards the potential impacts to the bridges have been identified, and commentary provided to whether or not it is likely to effect standard bridge design for the replacement bridges. Where a bridge is initially assessed to be vulnerable to a potential impact, it is carried through to a more detailed risk assessment in section 8. The preliminary screening is shown in Table 7.1.

Table 7.1 Preliminary Risk Screening

Risk No	Hazard	Potential impact	Description	Vulnerable Bridge site, Yes or No (Y/N)									
				Medraukutu	Lami	Navutu	Vunitogoloa	Viseisei	Vitawa	Navola	Matawalu	Sabeto	Lomolomo
Present Day Hazards													
1	Temperature / heat wave	Unmanaged thermal expansion.	Unlikely to impact standard bridge design.	N	N	N	N	N	N	N	N	N	N
2	Drought	Unmanaged thermal expansion.	Unlikely to impact approach and standard bridge design.	N	N	N	N	N	N	N	N	N	N
3	River flows	Scour of bridge piers and abutments.	All bridge design to consider scour in the design assessment.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Catchment-based flooding	Raised water level, bridge becomes struck by debris and/or inundated.	All bridge design to consider freeboard and debris.	Y	N	Y	Y	Y	Y	Y	N	N	Y
5	Tidal variation	High tides inundating bridge or approach roads.	All bridge design to consider freeboard and debris. Risk is captured in extreme sea levels.	N	N	N	N	N	N	N	N	N	N
6	Waves	Wave overtopping and forces on structure	Bridge design to consider freeboard from storm tide level and wave height. Wave forces should be further assessed.	Y	Y	N	N	N	N	Y	N	N	N
7	Extreme sea levels	Raised water level, bridge becomes inundated.	All bridges are close to the shoreline and extreme sea level should be further assessed.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Tropical cyclone	Wind forces on structure.	All bridges are likely to be impacted by tropical cyclones.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
9	Earthquake	Earthquake damage to structure	All bridge design to consider earthquake loading.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Risk No	Hazard	Potential impact	Description	Vulnerable Bridge site, Yes or No (Y/N)									
				Medraukutu	Lami	Navutu	Vunitogoloa	Viseisei	Vitawa	Navola	Matawalu	Sabeto	Lomolomo
10	Tsunami	Raised water level, bridge becomes struck by debris from downstream direction and/or inundated.	Chance that debris being pushed upstream impact the bridge.	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
11	Landslides	Approach roads or bridge becomes damaged or buried by landslide.	Unlikely to impact standard bridge design but slope stabilisation may be considered.	N	N	N	N	N	N	Y	N	N	N
Climate Change Related Hazards													
12	Increased temperatures / incidence of heatwaves	Unmanaged thermal expansion.	Unlikely to impact standard bridge design.	N	N	N	N	N	N	N	N	N	N
13	Increased river flows	Scour of bridge piers and abutments.	Higher intensity rainfall events resulting in increased river flows. All bridge design to consider scour in the design assessment.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
14	Increased catchment-based flooding	Raised water level, bridge becomes struck by debris and/or inundated.	Higher intensity of rainfall events, design events becoming more regular. All bridge design to consider freeboard and debris.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
15	Sea level rise	High tides inundating bridge or approach roads.	Increase tide levels. Increased sea level which elevates river level during floods.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
16	Waves	Wave overtopping and forces on structure.	Higher mean sea level increasing exposure to waves.	Y	Y	N	N	N	N	N	N	N	N

Risk No	Hazard	Potential impact	Description	Vulnerable Bridge site, Yes or No (Y/N)									
				Medraukutu	Lami	Navutu	Vunitogoloa	Viseisei	Vitawa	Navola	Matawalu	Sabeto	Lomolomo
17	Increased extreme sea levels	Raised water level, bridge becomes inundated.	All bridges are close to the shoreline and extreme sea level should be further assessed.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
18	Increased tropical cyclone intensity	Increased wind forces on structure.	All bridges are likely to be impacted by increased wind speed.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
19	Increased exposure to tsunami	Sea level rise increasing exposure to tsunami.	Chance that debris being pushed upstream impact the bridge.	Y	Y	Y	Y	Y	Y	Y	Y	Y	N

7.2 Summary of Medium or High Risks

Based on the preliminary screening, the following hazards will require further consideration for each of the bridges in a detailed risk assessment:

- Cyclonic or severe wind
- Wave impact
- Increased water level-based hazards
  - River flows
  - Catchment-based flooding
  - Extreme sea levels
- Tropical cyclones
- Scour based hazards
- Geophysical based hazards:
  - Earthquakes and liquefaction
  - Tsunami

Medraukutu and Lami Bridge are the only bridges exposed to wave action and coastal erosion, which should be considered in a detailed risk assessment and bridge scour allowances.

Navola is the only bridge likely to be impacted by a landslide which should be considered in a detailed risk assessment.

8 Risk Assessment

A risk rating for identified hazards for each priority 1 bridge (refer to Section 7) was carried out in accordance with AS 5334 (2013). The risk rating is defined in terms of measures of consequences, their likelihood and how these can be combined to express a level to risk. A qualitative estimate of likelihoods and consequences is conducted according to AS 5334 guidance and is summarised in Table 8.1.

The likelihood of hazard ranges from “Almost Certain,” where the event is on-going or is expected to occur during the following year, to “Very Unlikely” events, with return periods in excess of 200 years, thus having a low probability of occurring in a person’s lifetime.

A consequence of the occurrence of hazard ranges from “Insignificant”, where there is a minor inconvenience and some delays (hours), to “Catastrophic,” where widespread infrastructure is completely destroyed and there are multiple fatalities and extreme delays (years) due to the reconstruction of multiple infrastructure.

The qualitative likelihood and consequences are then aligned to determine overall risk. This exercise is completed for each of the priority 1 bridges in the following section.

Table 8.1: Risk Rating Matrix

Likelihood	**Consequences**				
	Catastrophic	**Major**	**Moderate**	**Minor**	**Insignificant**
Almost certain	E	E	H	H	M
Very likely	E	H	H	M	L
Likely	E	H	M	L	L
Possible	H	H	L	L	V
Unlikely	H	M	L	V	V
Very unlikely	M	L	V	V	V

Legend: E = Extreme risk, requiring immediate solution; H = High risk issue requiring short term solution to reduce risk to acceptable levels; M = Moderate risk issue, broadly tolerable in short term, requiring implementing treatment plan to reduce risks; L = Low risk issue, acceptable in short to medium term, requiring action through routine maintenance of assets; V = Very low risk, acceptable, requiring management by normal local procedures.

It is noted that there are some potential climate risks that should be considered when developing the construction methodology, such as:

- Potential for limited access to fresh water
- Potential for salt spray across the bridge site
- Potential for localised site flooding should an extreme event occur during construction
- Potential for varying daily temperatures, including extremes during construction

8.1 Bridge ID 2905 – Medraukutu

Table 8.2 identifies the key risk posed to the development of Medraukutu Bridge design.

Table 8.2: Bridge ID 2905 – Medraukutu Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Wave impact	Likely to be exposed to small wind waves within Suva Harbour.	Likely	Minor impact on bridge design compared to water flows and within standard bridge design practice.	Minor	L
Increased Water Level-based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour based hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Coastal erosion	Likely to be exposed to waves within Suva Harbour.	Likely	Minor impact on bridge design compared to water flows. Bridge design to include scour protection.	Minor	L
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.2 Bridge ID 2904 – Lami

Table 8.3 identifies the key risk posed to the development of Lami Bridge design.

Table 8.3: Bridge ID 2904 – Lami Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Wave impact	Likely to be exposed to small wind waves within Suva Harbour.	Likely	Minor impact on bridge design compared to water flows and within standard bridge design practice.	Minor	L
Increased Water Level-based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Coastal erosion	Likely to be exposed to waves within Suva Harbour.	Likely	Minor impact on bridge design compared to water flows. Bridge design to include scour protection.	Minor	L
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.3 Bridge ID 1602 – Navutu

Table 8.4 identifies the key risk posed to the development of Navutu Bridge design.

Table 8.4: Bridge ID 1602 – Navutu Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.4 Bridge ID 1104 – Vunitogoloa

Table 8.5 identifies the key risk posed to the development of Vunitogoloa Bridge design.

Table 8.5: Bridge ID 1104 – Vunitogoloa Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate extreme sea levels.	Moderate	H
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.5 Bridge ID 1415 – Visesei

Table 8.6 identifies the key risk posed to the development of Visesei Bridge design.

Table 8.6: Bridge ID 1415 – Visesei Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate extreme sea levels.	Moderate	H
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.6 Bridge ID 1107 – Vitawa

Table 8.7 identifies the key risk posed to the development of Vitawa Bridge design.

Table 8.7: Bridge ID 1107 – Vitawa Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.7 Bridge ID 1616 – Navola

Table 8.8 identifies the key risk posed to the development of Navola Bridge design.

Table 8.8: Bridge ID 1616 – Navola Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Coastal erosion	Unlikely that significant waves will propagate up the river channel.	Unlikely	Minor impact on bridge design compared to water flows. Bridge design to include scour protection.	Minor	V
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer approved Design Criteria.	NA	NA
Landslides	Possible to occur within the bridges design life.	Possible	Design of western approach hill cut to consider landslide.	Moderate	H

8.8 Bridge ID 1405 – Matawalu

Table 8.9 identifies the key risk posed to the development of Matawalu Bridge design.

Table 8.9: Bridge ID 1405 – Matawalu Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.9 Bridge ID 1419 – Sabeto

Table 8.10 identifies the key risk posed to the development of Sabeto Bridge design.

Table 8.10: Bridge ID 1419 – Sabeto Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.10 Bridge ID 1416 – Lomolomo

Table 8.11 identifies the key risk posed to the development of Lomolomo Bridge design.

Table 8.11: Bridge ID 1416 – Lomolomo Bridge Estimates of Likelihoods and Consequences for the Identified Hazards to Determine Risk

Hazard	Likelihood		Consequence		Risk
	Description	Rating	Description	Rating	
Cyclonic or severe wind	Cyclonic winds are likely to occur.	Likely	Significant for bridge users but within standard bridge design practice.	Minor	L
Increased Water Level-Based Hazards					
Catchment-based flooding	Very likely to occur within the bridges design life.	Very Likely	Bridge design to accommodate flow effects and debris impact.	Major	H
Extreme sea levels	Likely to occur within the bridges design life.	Likely	Bridge design to accommodate extreme sea levels.	Moderate	M
Scour Based Hazards					
River flows	Very likely to occur within the bridges design life.	Very Likely	Bridge design to include scour protection.	Major	H
Geophysical Based Hazards					
Earthquake	Likely to occur within the bridges design life.	Very Likely	Bridge design to consider earthquakes within standard bridge design practice.	Major	H
Liquefaction	Earthquakes very likely to occur but current ground conditions are unknown.	Very Likely	Bridge design to consider liquefaction.	Major	H
Tsunami	Possible to occur within the bridges design life.	Possible	Design for tsunami excluded from the requirements. Refer to approved Design Criteria.	NA	NA

8.11 Conclusions

Bridge replacement locations will be either at the same location as the existing bridge or on one side of the existing bridge. New bridge alignment options will have different bridge openings, orientations to the waterway and exposure to catchment-based flooding and coastal hazards. The ADB has established CRVA and DRA processes that extend from the initial screening through to detailed assessments and implementation of adaptation and mitigation options for the project. Based on the screening, the main natural hazards posing risks to new bridge alignment options to be:

- **Catchment-based flooding.** The effect of flood on new bridge alignment varies depending on bridge opening, skew angle, ground topography and other aspects. Options that allow flexibility in the size of the bridge opening and no or low skew to the waterway are preferred. In addition, options with lesser risk of erosion, scour and debris blockage are favoured.
- **Coastal hazards.** Alignment options protected by a landmass from direct exposure to wave and storm surge impacts and alignment options with a lesser risk of wave-induced erosion are preferred.

- **Earthquake.** Due to the proximity of bridge replacement alignment options at each site, their exposure to earthquakes is expected to be similar. However, at some sites, geotechnical conditions may vary between options due to a steeply dipping rock face or other variations in ground conditions. Alignments with more favourable ground conditions are preferred. This includes options with less risk of earthquake induced settlement and lateral displacement.

9 Design Recommendations

Table 9.1 identifies the critical design information for the design process. The design recommendations are recommendations resulting from the CRVA and DRA and should be considered on a bridge-by-bridge basis. It is assumed the bridge design will follow relevant standards. The recommendations presented here should be used as supportive information to the design process.

Table 9.1 Recommendations for Design

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
Medraukutu	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 2.5mRL noting that sea level dominated flood level is 2.6mRL.	Bridge soffit is set above the SLS2 flood level + 1.2m freeboard.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 2.8mRL noting that sea level dominated flood level is 3.0mRL.	Bridge soffit level is set over 0.6m higher than the ULS flood level providing clearance from ULS flooding therefore the superstructure is not design for flood and debris loading.	Full adoption, refer to design report for more information.
	Scour protection design to consider: • 1.41m/s design flow velocity at 3.31m average depth. • Wave height 1.81m with a period of 8s.	Scour protection in the form of rock bags placed at the abutments and base of piers.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures are required for the bridge's integrity. Full adoption, refer to design report for more information.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Lami	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River and sea dominated flood level for SLS2 is 2.8mRL.	Bridge soffit is set above the SLS2 flood level + 1.2m freeboard.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 3.2mRL noting that sea level dominated flood level is 3.1mRL.	Bridge soffit level is set over 0.6m higher than the ULS flood level providing clearance from ULS flooding therefore the superstructure is not design for flood and debris loading.	Full adoption, refer to design report for more information.
	Scour protection design to consider: • 5.0m/s design flow velocity at 4.2m average depth. • Wave height 1.91m with a period of 9s.	Scour protection in the form of rock bags placed at the abutments and base of piers.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures are required for the bridge's integrity. Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
Navutu	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 4.0mRL noting that sea level dominated flood level is 4.1mRL.	The soffit of the permanent bridge has been placed above SLS2 flood event of 4.0m RL plus 0.6m minimum freeboard. Actual freeboard achieved is 1.0m for the SLS2 river dominated event, to the lowest portion of the bridge soffit at the west abutment (5.0 mRL). Note, the soffit of the permanent bridge is 200 mm higher at the midspan, compared to at the lowest point of the bridge soffit at the west abutment.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 4.8mRL noting that sea level dominated flood level is 5.0mRL.	Minimum soffit level of approximately 5.0m RL.	Partial adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact. Refer to design report for more information.
	Scour protection design to consider: • Pier hydraulic conditions: 2.24m/s design flow velocity at 4.2m average depth. • Abutment hydraulic conditions: 0.91m/s design flow velocity at 2.13m average depth.	Scour protection in the form of rock rip rap placed at the abutments and across the channel.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures is required for the bridge's integrity.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
			Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Vunitogoloa	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River and sea dominated flood level for SLS2 is 4.0mRL.	Deck level at 4.0mRL is approximately equal to the SLS2 flood level.	No adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact. Refer to design report for justification.
	For ULS the soffit level is to be greater than ULS maximum water level. Sea dominated flood level for ULS is 4.8mRL.	Deck level at 4.0mRL is approximately equal to the SLS2 flood level therefore lower than ULS water level.	No adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact. Refer to design report for justification.
	Scour protection design to consider: • Pier hydraulic conditions: 1.6m/s design flow velocity at 4.3m average depth. • Abutment hydraulic conditions: 1.0m/s design flow velocity at 3.7m average depth.	Scour protection in the form of rock rip rap placed at the abutments and across the channel.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures is required for the bridge's integrity.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
			Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Vunitogoloa Temporary	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS1 is 3.5mRL.	Deck level is set at 4.6mRL with an approximate soffit level of 3.9mRL therefore a freeboard of 0.4m is achieved.	Partial adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. Sea dominated flood level for ULS is 3.9mRL.	Soffit level is set at 3.9mRL.	The temporary bridge superstructure has not been designed to resist ULS flood water forces. Refer to design report for more information.
	Scour protection design to consider: • 1.60m/s design flow velocity at 3.20m average depth.	Scour protection in the form of 2-tonne rock bags placed at the abutments atop the embankment.	Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	The temporary bridge foundations are not designed to withstand lateral spreading due to liquefaction.	Following a seismic event, the temporary bridge, including abutments will need to be revealed and / or repositioned and structural repair of the bridge deck may be required.
Viseisei	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 3.1mRL noting that sea level dominated flood level is 3.2mRL.	Bridge soffit level varies along the bridge length from 4.0mRL at Pier A to 3.5mRL at the eastern end. The achieved freeboard is greater than 0.6m for most of the bridge length but drops to 0.4m at the eastern end of the bridge.	Partial adoption, refer to design report for more information.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 3.6mRL noting that sea level dominated flood level is 4.2mRL.	The eastern end of the bridge is estimated to be submerged approximately 100mm during river flow dominated flooding and 700mm during tidal dominated flooding.	Partial adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact. Refer to design report for more information
	Scour protection design to consider: • 4.6m/s design flow velocity at 6.50m average depth.	Scour protection in the form of rock bags placed at the abutments and base of piers.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures are required for the bridge's integrity. Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Vitawa	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 4.6mRL noting that sea level dominated flood level is 4.7mRL.	Soffit level is approximately equal to the SLS2 flood level.	No adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
			Refer to design report for justification.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 5.8mRL.	Deck level with cross fall at 5.8mRL is approximately equal to the SLS2 flood level therefore lower than ULS water level.	No adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact. Refer to design report for justification.
	Scour protection design to consider: • Pier hydraulic conditions: 1.38m/s design flow velocity at 3.65m average depth. • Abutment hydraulic conditions: 1.38m/s design flow velocity at 2.13m average depth.	Scour protection in the form of rock rip rap placed at the abutments and across the channel.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures is required for the bridge's integrity. Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Vitawa Temporary	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS1 is 3.9mRL.	Temporary diversion road pipe culvert crossing is to be designed the contractor and approved by the engineer. Refer to design report for more information.	

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
	For ULS the soffit level is to be greater than ULS maximum water level. Sea dominated flood level for ULS is 5.3mRL.		
	Scour protection design to consider: N/A		
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.		
Navola	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River and sea dominated flood level for SLS2 is 3.6mRL noting that sea level dominated flood level is 3.6mRL.	Bridge soffit is set above the SLS2 flood level + 1.2m freeboard.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 3.9mRL noting that sea level dominated flood level is 3.8mRL.	Bridge soffit level is set over 1.0m higher than the ULS flood level providing clearance from ULS flooding therefore the superstructure is not design for flood and debris loading.	Full adoption, refer to design report for more information.
	Scour protection design to consider: • Pier hydraulic conditions: 1.2m/s design flow velocity at 2.9m depth. • Abutment hydraulic conditions: 0.9m/s design flow velocity at 2.5m average depth.	Scour protection in the form of rock rip rap placed at the abutments and across the channel.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures are required for the bridge's integrity.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
			Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
	Design of western approach hill cut to consider landslide.	The road widening requires significant excavation into the existing slope. A rock cut design feature is included.	Full adoption, refer to design report and geotechnical report for details.
Matawalu	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 4.3mRL.	Bridge soffit is set above the SLS2 flood level + 1.2m freeboard.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 4.7mRL.	Bridge soffit level is set over 0.6m higher than the ULS flood level providing clearance from ULS flooding therefore the superstructure is not design for flood and debris loading.	Full adoption, refer to design report for more information.
	Scour protection design to consider: • Pier hydraulic conditions: 1.06m/s design flow velocity at 6.5m depth. • Abutment hydraulic conditions: 1.06m/s design flow velocity at 4.42m average depth.	Scour protection in the form of rock rip rap placed at the abutments and at piers.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures is required for the bridge's integrity. Full adoption, refer to design report for more information.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Matawalu Temporary	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS1 is 3.3mRL.	Bridge soffit is set above the SLS1 flood level + 1.2m freeboard.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. Sea dominated flood level for ULS is 3.9mRL.	Soffit level is set at 4.8mRL providing over 0.6m clearance during ULS flood levels.	Full adoption, refer to design report for more information.
	Scour protection design to consider: • 1.6m/s design flow velocity at 4.8m average depth.	Scour protection in the form of 2-tonne rock bags placed at the abutments atop the embankment.	Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	The temporary bridge foundations are not designed to withstand lateral spreading due to liquefaction.	Following a seismic event, the temporary bridge, including abutments will need to be revealed and / or repositioned and structural repair of the bridge deck may be required. Refer to design report and geotechnical report for more information.
Sabeto	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 3.8mRL.	Bridge soffit is set above the SLS2 flood level + 1.2m freeboard.	Full adoption, refer to design report for more information.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for ULS is 4.2mRL.	Bridge soffit level is set over 0.6m higher than the ULS flood level providing clearance from ULS flooding therefore the superstructure is not	Full adoption, refer to design report for more information.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
		design for flood and debris loading.	
	Scour protection design to consider: • Pier hydraulic conditions: 2.1m/s design flow velocity at 6.56m depth. • Abutment hydraulic conditions: 2.10m/s design flow velocity at 5.32m average depth.	Scour protection in the form of rock rip rap placed at the abutments and outer piers.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures is required for the bridge's integrity. Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.
Lomolomo	For SLS the soffit level is to be set at the SLS2 maximum water level plus an allowance for freeboard of 0.6m or 1.2m depending on debris potential. River dominated flood level for SLS2 is 3.2mRL noting that sea level dominated flood level is 3.1mRL.	Soffit level is at 2.3mRL and submerged during SLS2 conditions.	No adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact. Refer to design report for justification.
	For ULS the soffit level is to be greater than ULS maximum water level. River dominated flood level for SLS2 is 3.3mRL noting that sea level dominated flood level is 4.1mRL.	Deck level with cross fall is at 3.5mRL therefore submerged during river and sea dominated flood levels.	No adoption. The superstructure is designed for flood and debris loading. Maintenance or repair may be required following a major flooding event due to debris or log impact.

Bridge	Recommendations for Design	Final Design Feature	Justification for Full, Partial and No Adoption
			Refer to design report for justification.
	Scour protection design to consider: • Pier hydraulic conditions: 1.30m/s design flow velocity at 4.00m average depth. • Abutment hydraulic conditions: 0.70m/s design flow velocity at 3.00m average depth.	Scour protection in the form of rock rip rap placed at the abutments and across the channel.	Analysis was performed of the scour depths in relation to the structural capacity of the piers and abutments, it has been determined that the existing elements would be insufficient to withstand the additional forces exerted by the estimated scour depths. Consequently, the implementation of scour protection measures is required for the bridge's integrity. Full adoption, refer to design report for more information.
	Earthquake design magnitude not less than M 7.1 and must consider the effects of liquefaction.	A lattice type ground improvement structure is included to provide resilience against seismic shaking.	Design considers an earthquake magnitude of M 7.5.

9.1 Adaptation Cost Estimates

Adaptation options were identified based on the design features outlined in Table 9.2. These features encompassed the bridge structure, approach embankments, scour protection, and ground improvement structures, all of which entail costs directly related to addressing climate change and disaster resilience. For each adaptation activity an estimate of associated adaptation costs is provided along with justification.

Table 9.2 Adaptation Cost Estimate

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
B01 Medraukutu Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.91	Design of new bridge structure adopted a higher deck level to provide freeboard clearance to the 1/100yr SLS and 1/1000yr ULS flood events.

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$2.71	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$4.61	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments. Design of scour protection to provide resilience against 1/100yr wave induced erosion during extreme storm events.
Provision of ground improvement structure	Earthquake and liquefaction	$4.61	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B02 Lami Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.23	Design of new bridge structure adopted a higher deck level to provide freeboard clearance to the 1/100yr SLS and 1/1000yr ULS flood events.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$0.33	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$2.74	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
			Design of scour protection to provide resilience against 1/100yr wave induced erosion during extreme storm events.
Provision of ground improvement structure	Earthquake and liquefaction	$5.94	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B03 Navutu Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$0.57	The design of the new bridge structure incorporated a raised soffit level to provide adequate freeboard clearance for the 1/100yr SLS flood event. However, new soffit level aligns closely with the ULS flood level when dominated by sea level. Consequently, the superstructure is designed to withstand flood and debris loadings.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$0.65	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.25	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$4.79	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
B04 Vunitogoloa Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$0.97	The bridge soffit was raised to the maximum level practicable, yet it does not attain a level that provides freeboard clearance for 1/100 SLS and 1/1000 ULS floods. As a result, the bridge is designed to withstand flood and debris loading on the superstructure.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$0.91	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.37	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$5.59	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B05 Visesei Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.25	The design of the new bridge structure incorporated a raised soffit level to provide adequate freeboard clearance for the 1/100yr SLS flood event. However, new soffit level aligns closely with the ULS flood level when dominated by sea level. Consequently, the superstructure is designed to withstand flood and debris loadings.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge	$5.27	Design of a higher finished road level to accommodate elevated road approaches, aligning with

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
	levels. The road approach is raised accordingly		the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.30	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$6.65	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B06 Vitawa Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.54	The bridge soffit was raised to the maximum level practicable, yet it does not attain a level that provides freeboard clearance for 1/100 SLS and 1/1000 ULS floods. As a result, the bridge is designed to withstand flood and debris loading on the superstructure.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$2.22	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.26	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$3.45	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
B07 Navola Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.38	Design of new bridge structure which adopted a higher deck level to provide freeboard clearance to the 1/100yr SLS and 1/1000yr ULS flood events.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$3.64	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.3	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$1.77	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B08 Matawalu Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.31	Design of new bridge structure which adopted a higher deck level to provide freeboard clearance to the 1/100yr SLS and 1/1000yr ULS flood events.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$2.16	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.3	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
Provision of ground improvement structure	Earthquake and liquefaction	$5.69	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B09 Sabeto Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$0.62	Design of new bridge structure which adopted a higher deck level to provide freeboard clearance to the 1/100yr SLS and 1/1000yr ULS flood events.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge levels. The road approach is raised accordingly	$2.04	Design of a higher finished road level to accommodate elevated road approaches, aligning with the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.32	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$6.13	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.
B10 Lomolomo Bridge			
Allowance in the new bridge for raising the soffit level	Sea level rise and increase in rainfall intensity resulting in increased flood levels	$1.00	The bridge soffit was raised to the maximum level practicable, yet it does not attain a level that provides freeboard clearance for 1/100 SLS and 1/1000 ULS floods. As a result, the bridge is designed to withstand flood and debris loading on the superstructure.
Allowance in the new road approach for the increase in bridge level	Sea level rise and increase in rainfall intensity resulting in increased flood levels and raising the bridge	$2.64	Design of a higher finished road level to accommodate elevated road approaches, aligning with

Adaptation Activity	Target Climate/Disaster Risk	Estimated Adaptation Costs ($ million)	Adaptation Finance Justification
	levels. The road approach is raised accordingly		the raised bridge level to enhance flood resilience.
Provision of scour protection	Flood induced erosion	$0.39	Design of scour protection to enhance resilience against erosion during significant flood events, encompassing both the 1/100yr SLS and 1/1000yr ULS floods, protecting the bridge piers and abutments.
Provision of ground improvement structure	Earthquake and liquefaction	$4.08	Design a ground improvement structure which reduces liquefaction and seismic movements to improve structural resilience to large seismic events including the 1/1000yr DCLS earthquake.

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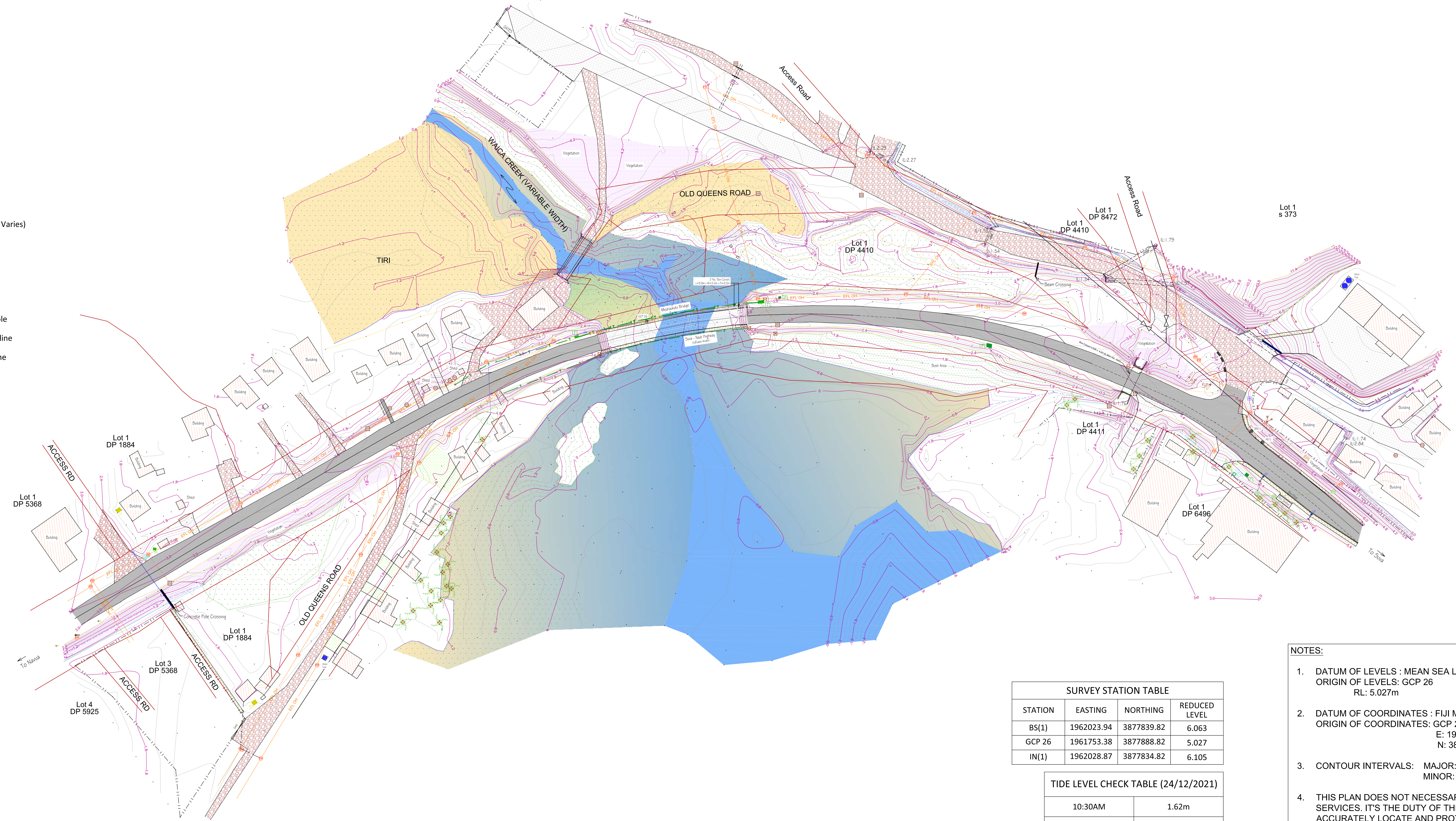
A

Appendix A – Topographical Survey

LEGEND

- Contour Major
- Contour Minor
- Top Bank
- Bottom Bank
- Drain Invert Flow Direction
- Power Pole
- Septic Tank
- Telecom Chamber
- Sign Post
- Fence
- Seal Formation
- Graveled Formation
- Concrete Formation
- Tiri Land
- Concrete Footpath
- Water Valve
- Road Center Line
- Utilities Chamber
- Gully Pit
- Cross Culvert (Width Varies)
- Marker Post
- Boundary Line
- Fly Stay Pole
- Stay Wire
- Residential Power Pole
- Overhead EFL Powerline
- Residential Power Line
- Concrete Plinth
- Water Meter
- Water Valve
- Meter Box on Pole
- Drain Steel Cover
- Culvert Invert Level
- Telecom Line
- Grass Driveway
- Telecom Pole
- Vegetation



SURVEY STATION TABLE			
STATION	EASTING	NORTHING	REDUCED LEVEL
BS(1)	1962023.94	3877839.82	6.063
GCP 26	1961753.38	3877888.82	5.027
IN(1)	1962028.87	3877834.82	6.105

TIDE LEVEL CHECK TABLE (24/12/2021)	
10:30AM	1.62m
11:30AM	1.42m
12:30PM	1.21m
1:30PM	1.00m
2:30PM	0.80m
3:30PM	0.60m
4:30PM	0.40m

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: GCP 26
   RL: 5.027m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: GCP 26
   E: 1961753.38
   N: 3877888.82
3. CONTOUR INTERVALS: MAJOR: 1.00m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. WAICA CREEK IS NOT SUBJECT TO FLOODING.

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	KRISHNEEL LAL
SURVEY ASST	SHANVI LAL,TOMASI KORORUA,VILIAME ANTONIO
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SERONA FREMLIN
SURVEY INSTRUCTION	(SI) No SS 96/21
DATE OF SURVEY	07/01/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

Fiji Roads Authority
Level 4, Fiji Development Bank Building,
360 Victoria Parade, Suva, Fiji Islands.
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Phone (+679) 310 0114 | Fax (+679) 310 0044 |
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF MEDRAUKUTU BRIDGE

TIKINA: SUVA PROVINCE: REWA ISLAND: VITI LEVU

REQUEST FROM: BRIDGE & STRUCTURES

DATE OF REQUEST: 13/12/2021

Scales: 1:1000 @ A1

Drawing No.: FRA: SS 96/21

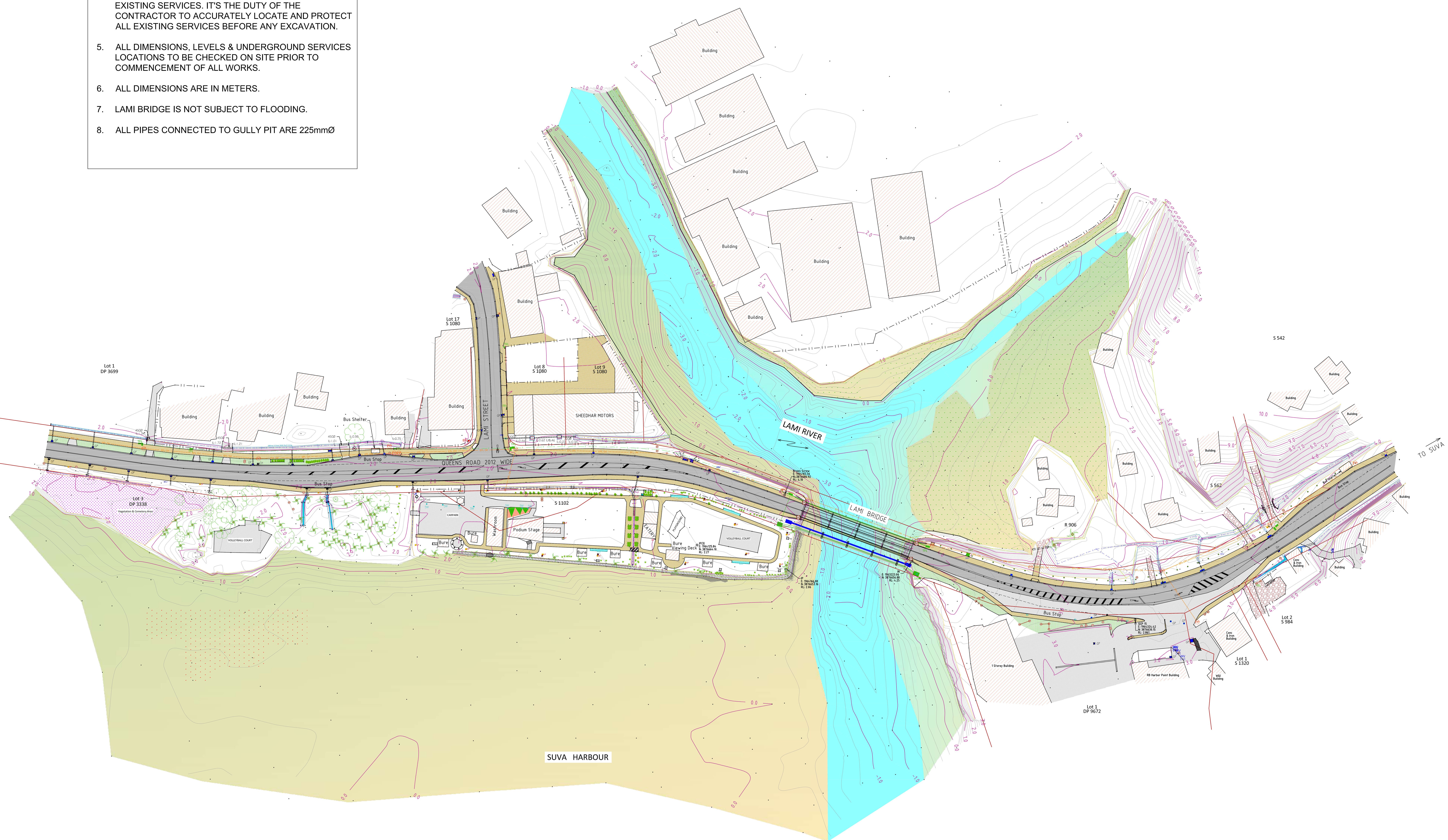
Rev.: 0

LEGEND

- 2.0 - Contour Major
- Contour Minor
- Top Bank
- Bottom Bank
- Drain Invert Flow Direction
- PP - Power Pole
- LP - Lamp Post with Power Box Steel cover & Solar Panel
- TC - Telecom Chamber
- MH - Manhole (sealed)
- GP - Gully Pit
- SP - Sign Post
- SP—SP - Sign Board
- Fence
- Seal Formation
- Graveled Formation
- Concrete Formation
- Tiri Land
- Concrete Footpath
- WV - Water Valve
- Road Marking
- SW - Stormwater Pit
- Fire Hydrant
- Hatch Sea
- Telecom Duct Line
- Grass Formation
- Boundary Line
- Water Meter
- CH - Utilities Chamber (sealed)
- Residential Electrical Pole
- GT - Gas Tank
- Gabion Basket
- Tyre Armour
- Rock Armour
- Newly Planted Tiri
- Marker Post

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: GCP 15
   RL: 2.861m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: GCP 15
   E: 1964324.42
   N: 3876630.15
3. CONTOUR INTERVALS: MAJOR: 1.0m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. LAMI BRIDGE IS NOT SUBJECT TO FLOODING.
8. ALL PIPES CONNECTED TO GULLY PIT ARE 225mmØ



TIDE LEVEL CHECK TABLE (24/12/2021)	
10:30AM	0.601m
11:30AM	0.588m
12:30PM	0.582m
1:30PM	0.395m
2:30PM	0.199m
3:30PM	0.184m

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	SAMISONI LEDUA
SURVEY ASST	SHANVI LAL, LEMEKI RAVAELE
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	AMEET KUMAR
SURVEY INSTRUCTION	(SI) No.SS 95/21
DATE OF SURVEY	07/01/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

Fiji Roads Authority
Level 4, Fiji Development Bank Building,
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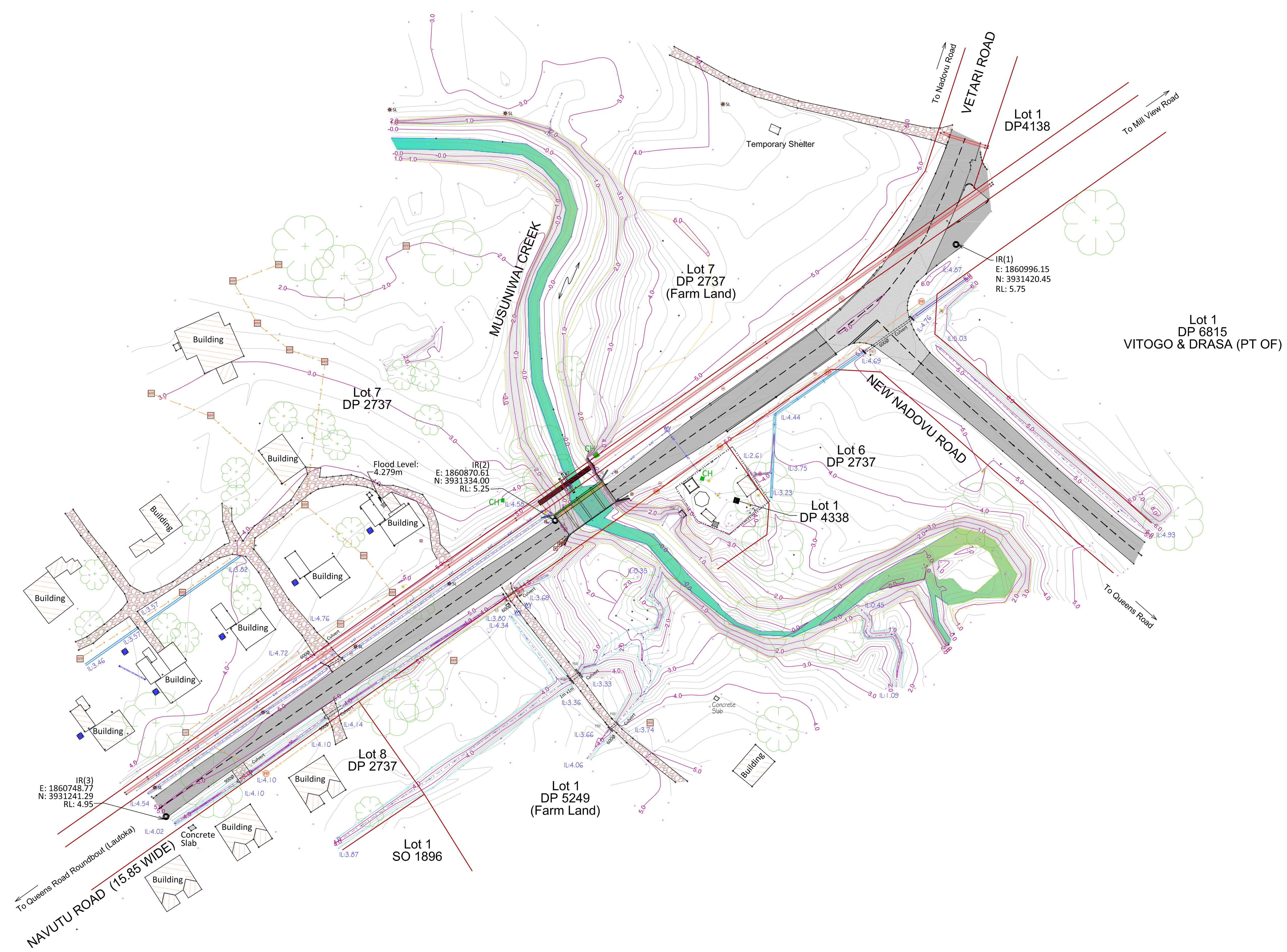
Phone (+679) 310 0114 | Fax (+679) 310 0044 |
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF LAMI BRIDGE

TIKINA: SUVA PROVINCE: REWA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGES & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 95/21
Rev.	0



LEGEND

- Contour Major
- Contour Minor
- Top of Bank
- Bottom of Bank
- PP - Power Pole
- 280mm V-Drain (Invert Flow)
- Concrete Trapezoidal Drain
- Sealed Formation
- Graveled Formation
- Concrete Footpath
- Concrete Bridge Deck or Pavement
- Concrete Culvert (Size Varies)
- WV - Water Valve
- CH - Utilities Chamber (Sealed)
- Railway Tracks
- RS - Road Sign
- RPP - Residential Power Pole
- HW - Headwall with Culvert
- SL - Street Light
- BMP - Bridge Marker Post
- MH - Sewer Manhole
- Marker Post
- Water Tank
- Gate

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: SS 6120(SO 3264)
   RL: 1.63m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SS 6120(SO 3264)
   E: 1860716.17
   N: 3932134.28
3. CONTOUR INTERVALS: MAJOR: 1.0m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. LOT 1, DP 4338: SEWERAGE TREATMENT PLANT
8. FLOOD LEVEL : 4.279m
9. SOFFIT LEVEL:
   FRA BRIDGE : 4.809m
   F.S.C BRIDGE : 4.601m
10. WATER LEVEL AT BRIDGE : 3.779m

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	KRISHNEEL LAL
SURVEY ASST	TOMASI KORORUA, VILIAME ANTONIO
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHAINEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 103/21
DATE OF SURVEY	09/01/2022
APPROVED	SHIRI NARAYAN
SURVEY SECTION	

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Level 4, Fiji Development Bank Building,
360 Victoria Parade, Suva, Fiji Islands.
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Phone (+679) 310 0114 | Fax (+679) 310 0044 |
email: shiri.narayan@fijiroads.org

DESCRIPTION:

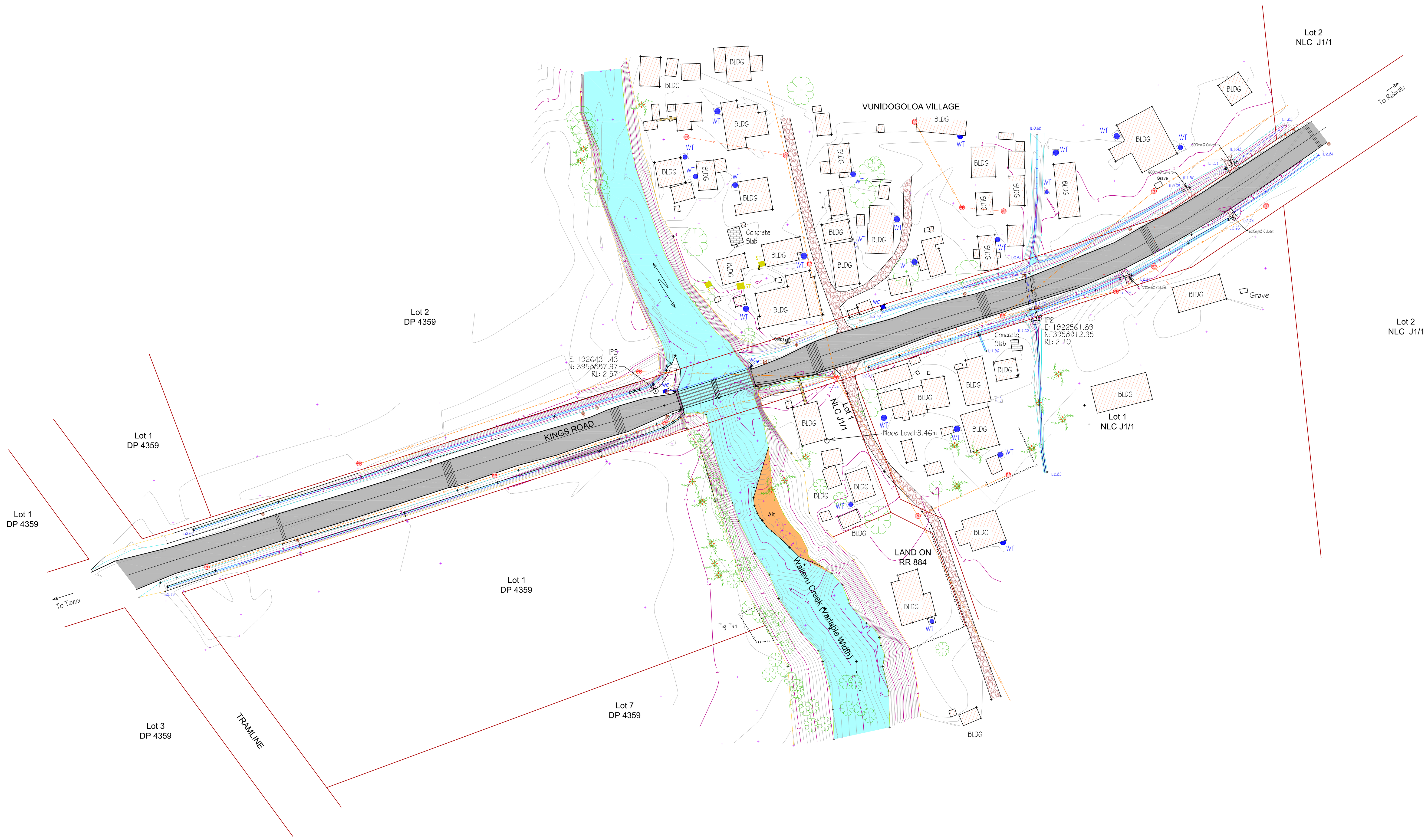
DETAILED TOPOGRAPHICAL SURVEY OF NAVUTU BRIDGE

TIKINA: VUDA PROVINCE: BA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGES & STRUCTURES
DATE OF REQUEST	31/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 103/21
Rev.	0

LEGEND

- Major Contour
- Minor Contour
- Top of Bank
- Bottom of Bank
- Street Lights
- Power Pole
- Residential Power Pole
- Seal Formation
- Graveled Formation
- Drain Invert
- Boundary Line
- Water Chamber
- Road Sign
- Marker Post
- Culvert Crossing
- Water Tank
- Septic Tank
- Residential Power Pole
- Overhead E.F.L Power Line
- Residential Power Line
- Water Main
- Open Earth Drain



NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: TUIDREKE TRIG
   RL: 258.363m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: TUIDEKE TRIG
   E: 1923090.42
   N: 3957826.13
3. CONTOUR INTERVALS: MAJOR: 1.00m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. SOFFIT LEVEL : 1.92m
8. FLOOD LEVEL : 3.46m

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	KRISHNEEL LAL
SURVEY ASST	SHANVI LAL,TOMASI KORORUA,VILIAME ANTONIO
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHANEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 101/21
DATE OF SURVEY	07/01/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

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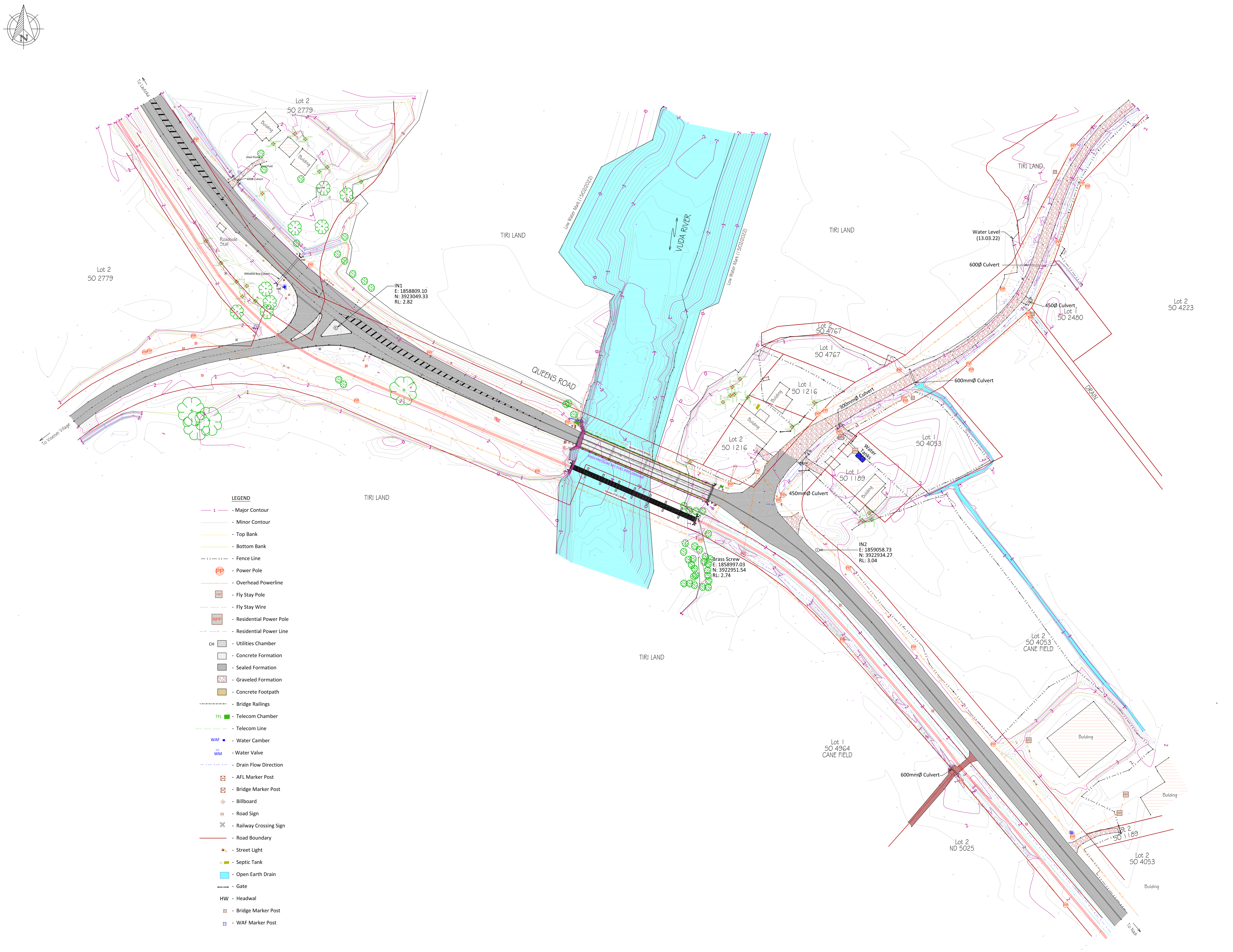
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF VUNITOGOLOA BRIDGE

TIKINA: RAKIRAKI PROVINCE: RA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGE & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 101/21
Rev.	0



NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: SS 3511 (SO 4242)
   RL: 41.729m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SS 3511 (SO 4242)
   E: 1860788.16
   N: 3921511.27
3. CONTOUR INTERVALS: MAJOR: 1.0m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. SOFFIT LEVEL : FRA BRIDGE (VISEISEI) : 1.47m
   FSC BRIDGE VISEISEI) : 1.36m
8. VISEISEI BRIDGE IS NOT SUBJECT TO FLOODING

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	KRISHNEEL LAL
SURVEY ASST	TOMASI & VILIAME
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHAINEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 26/22
DATE OF SURVEY	13/03/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

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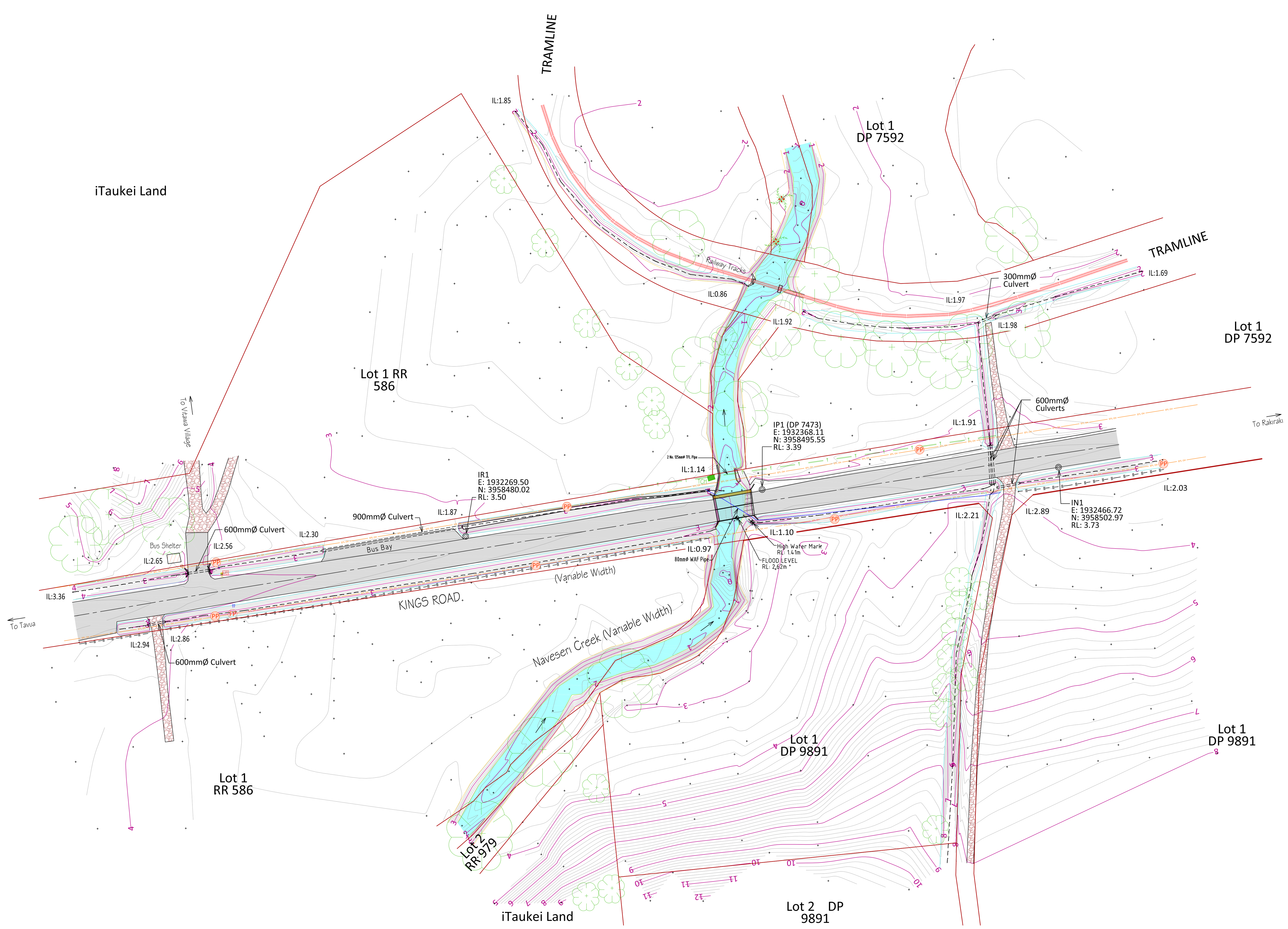
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF VISEISEI BRIDGE

TIKINA: VUDA PROVINCE: BA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGES & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 26/22
Rev.	0



LEGEND

- Contour Major
- Contour Minor
- Top of Bank
- Bottom of Bank
- PP - Power Pole
- Open Earth Drain (Invert Flow)
- CH - Water Authority Chamber
- Sealed Formation
- Graveled Formation
- Concrete Footpath
- Concrete Deck
- Fence
- Concrete Culvert
- SV - Sluice Valve
- MB - Power Meter Box
- SL - Street Light
- Creek Flow Direction
- TCH - Telecom Chamber
- Duct Telecom Line
- Boundary Line
- FP - Fly Stay pole
- IL:1.91 - Invert Level

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: SS 11556 (SO 3187)
   RL: 39.339m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SS 11556 (SO 3187)
   E: 1932945.78
   N: 3958300.58
3. CONTOUR INTERVALS: MAJOR: 1.00m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. SOFFIT LEVEL - 2.56m FROM RAILWAY TIMBER DECK. SOFFIT LEVEL FOR VITAWA - 2.57m

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	SAMISONI LEDUA
SURVEY ASST	SHANVI LAL, LEMEKI RAVAELE
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHAINEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 102/21
DATE OF SURVEY	07/01/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

Fiji Roads Authority
Level 4, Fiji Development Bank Building,
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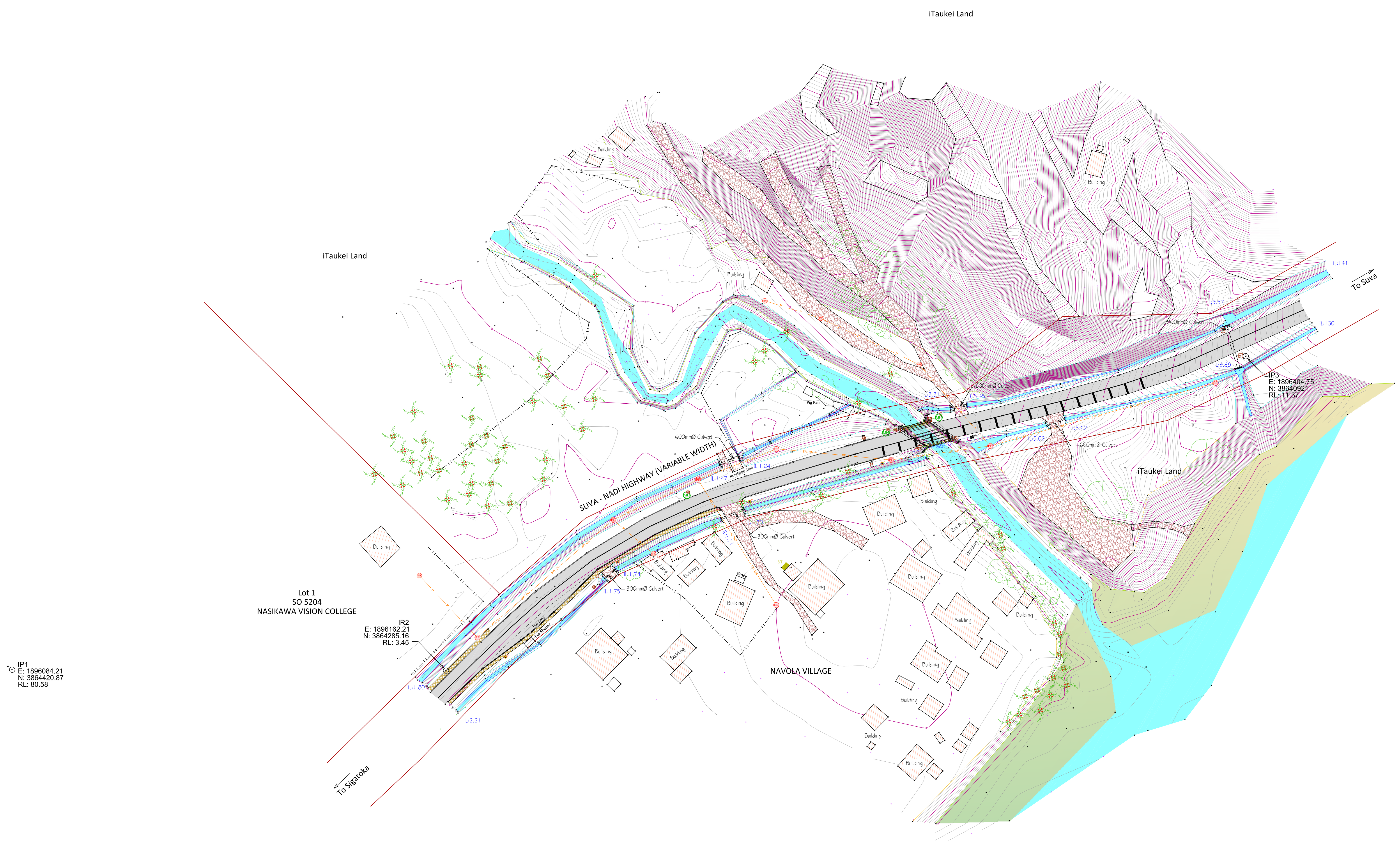
DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF VITAWA BRIDGE

TIKINA: RAKIRAKI PROVINCE: RA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGES & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 102/21
Rev.	0



LEGEND

- Major Contour
- Minor Contour
- Top of Bank
- Bottom of Bank
- Lamp Post
- Telecom Manhole
- Power Pole
- Seal Formation
- Graveled Formation
- Concrete Deck
- Concrete Footpath
- Drain Invert
- Fence Line
- Cross Culvert (Size Varies)
- Boundary Line
- Residential Power Pole
- EFL Overhead Powerline
- Water Authority Chamber
- Marker Post
- Road Sign
- Septic Tank
- Residential Power Pole
- Residential Power Line

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: IR(100) [FRA SI: SS 85/21]
   RL: 3.23m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SS 2800 (SO 901)
   E: 1892437.59
   N: 3865149.46
3. CONTOUR INTERVALS: MAJOR: 1m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. WATER LEVEL : 0.68m
8. SOFFIT LEVEL: 3.00m
9. NAVOLA BRIDGE IS NOT SUBJECT TO FLOODING

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	SHANVI LAL
SURVEY ASST	SAMISONI LEDUA, LEMEKI RAVAELE
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHAINEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 104/21
DATE OF SURVEY	09/01/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

Fiji Roads Authority
Level 4, Fiji Development Bank Building,
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Phone (+679) 310 0114 | Fax (+679) 310 0044 |
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF NAVOLA BRIDGE

TIKINA: BARAVI PROVINCE: NADROGA/NAVOSA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGE & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 104/21
Rev.	0

LEGEND

- Major Contour
- Minor Contour
- Power Pole
- Sign Post
- Road Sign (Billboards)
- Telecom Box
- Water Meter
- Top of Bank
- Bottom of Bank
- Drain Invert [Open Earth Drain]
- Railway
- Culverts (Size Varies)
- Boundary Line
- Sealed Formation
- Graveled Formation
- Fence Line
- Street Light Meter Box
- Marker Post
- Street Light
- Septic Tank
- Water Authority Marker Post
- Residential Power Pole
- Headwall
- WAF Chamber
- Water Main Line
- Bridge Railings
- Utilities Chamber
- Invert Level
- Overhead EFL Powerline
- Telecom Line

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: SS 3390 (SO 3540)
   RL:2.874m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SS 3390 (SO 3540)
   E: 1868690.04
   N: 3936449.72
3. CONTOUR INTERVALS: MAJOR: 1.0m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. FLOOD LEVEL: 4.95m
8. BRIDGE SOFFIT LEVEL:
   FRA Bridge (Matawalu) : 4.21m
   FSC Bridge (Matawalu) : 2.66m
9. BUILDING ON (SO 4666, SO 4705 & ND 5054) ARE PLOTTED FROM GOOGLE EARTH IMAGE.

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	SAMISONI LEDUA
SURVEY ASST	LEMEKI RAVAELE, SHANVI LAL
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
SURVEY INSTRUCTION	(SI) No.SS 99/21
DATE OF SURVEY	04/01/2022
APPROVED	SHIRI NARAYAN
SURVEY SECTION	

Fiji Roads Authority
Level 4, Fiji Development Bank Building,
360 Victoria Parade, Suva, Fiji Islands.
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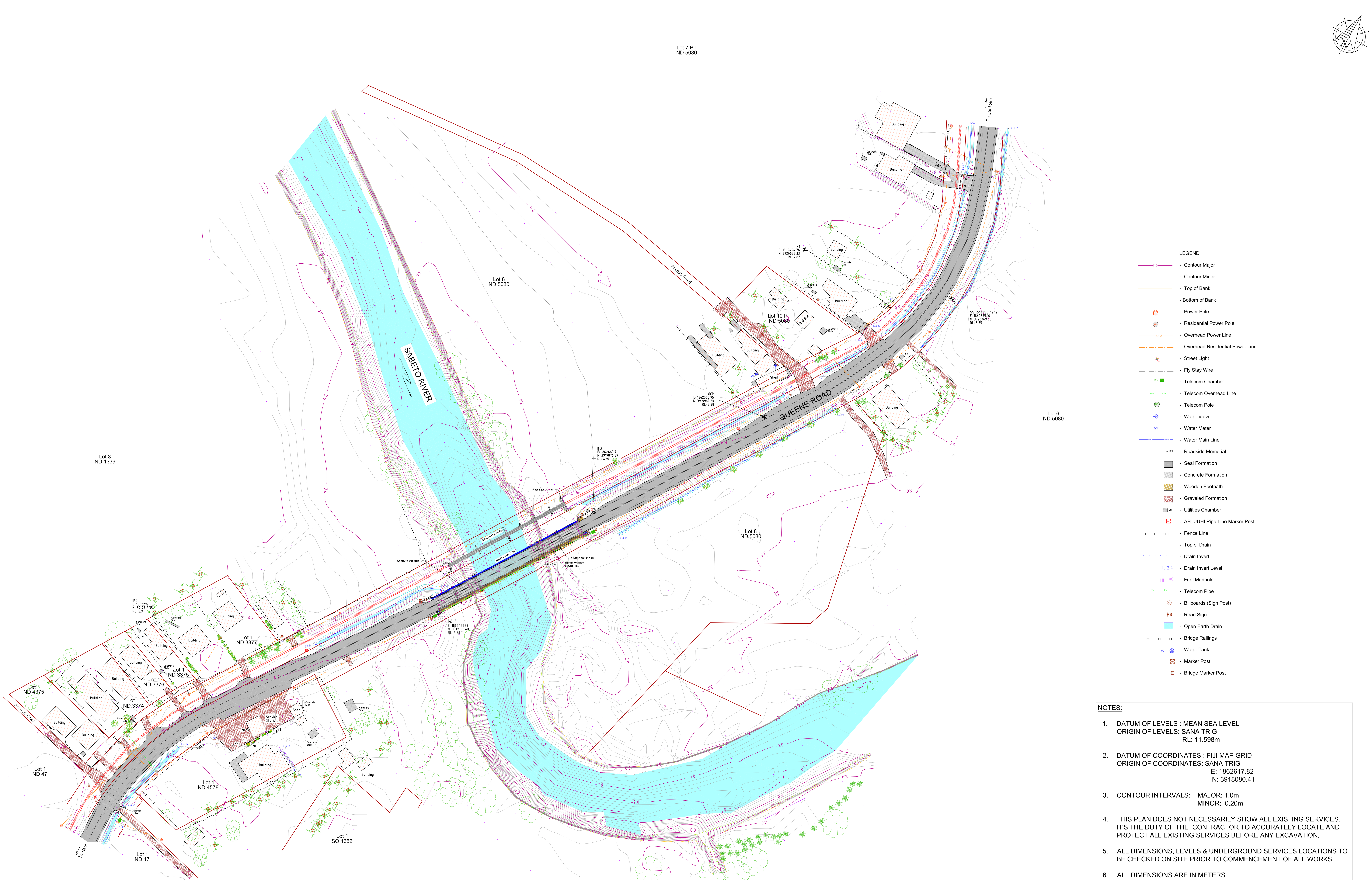
Phone (+679) 310 0114 | Fax (+679) 310 0044 |
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF MATAWALU BRIDGE

TIKINA: VUDA PROVINCE: BA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGES & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 100/21
Rev.	0



LEGEND

- Contour Major
- Contour Minor
- Top of Bank
- Bottom of Bank
- Power Pole
- Residential Power Pole
- Overhead Power Line
- Overhead Residential Power Line
- Street Light
- Fly Stay Wire
- Telecom Chamber
- Telecom Overhead Line
- Telecom Pole
- Water Valve
- Water Meter
- Water Main Line
- Roadside Memorial
- Seal Formation
- Concrete Formation
- Wooden Footpath
- Graveled Formation
- Utilities Chamber
- AFL JUHI Pipe Line Marker Post
- Fence Line
- Top of Drain
- Drain Invert
- Drain Invert Level
- Fuel Manhole
- Telecom Pipe
- Billboards (Sign Post)
- Road Sign
- Open Earth Drain
- Bridge Railings
- Water Tank
- Marker Post
- Bridge Marker Post

NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: SANA TRIG
   RL: 11.598m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SANA TRIG
   E: 1862617.82
   N: 3918080.41
3. CONTOUR INTERVALS: MAJOR: 1.0m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. SOFFIT LEVEL : FRA BRIDGE (SABETO) : 4.04m
   FSC BRIDGE (SABETO) : 3.53m
8. FLOOD LEVEL: Reduced Level = 3.80m
9. HIGH WATER MARK : Reduced Level = 0.33m (15/02/2022)

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	KRISHNEEL LAL & SAMISONI LEDUA
SURVEY ASST	SHANVI, LEMEKI, TOMASI & VILIAME
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHAINEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 25/22
DATE OF SURVEY	15/02/2022
APPROVED	SHIRI NARAYAN

SURVEY SECTION

Fiji Roads Authority
Level 4, Fiji Development Bank Building,
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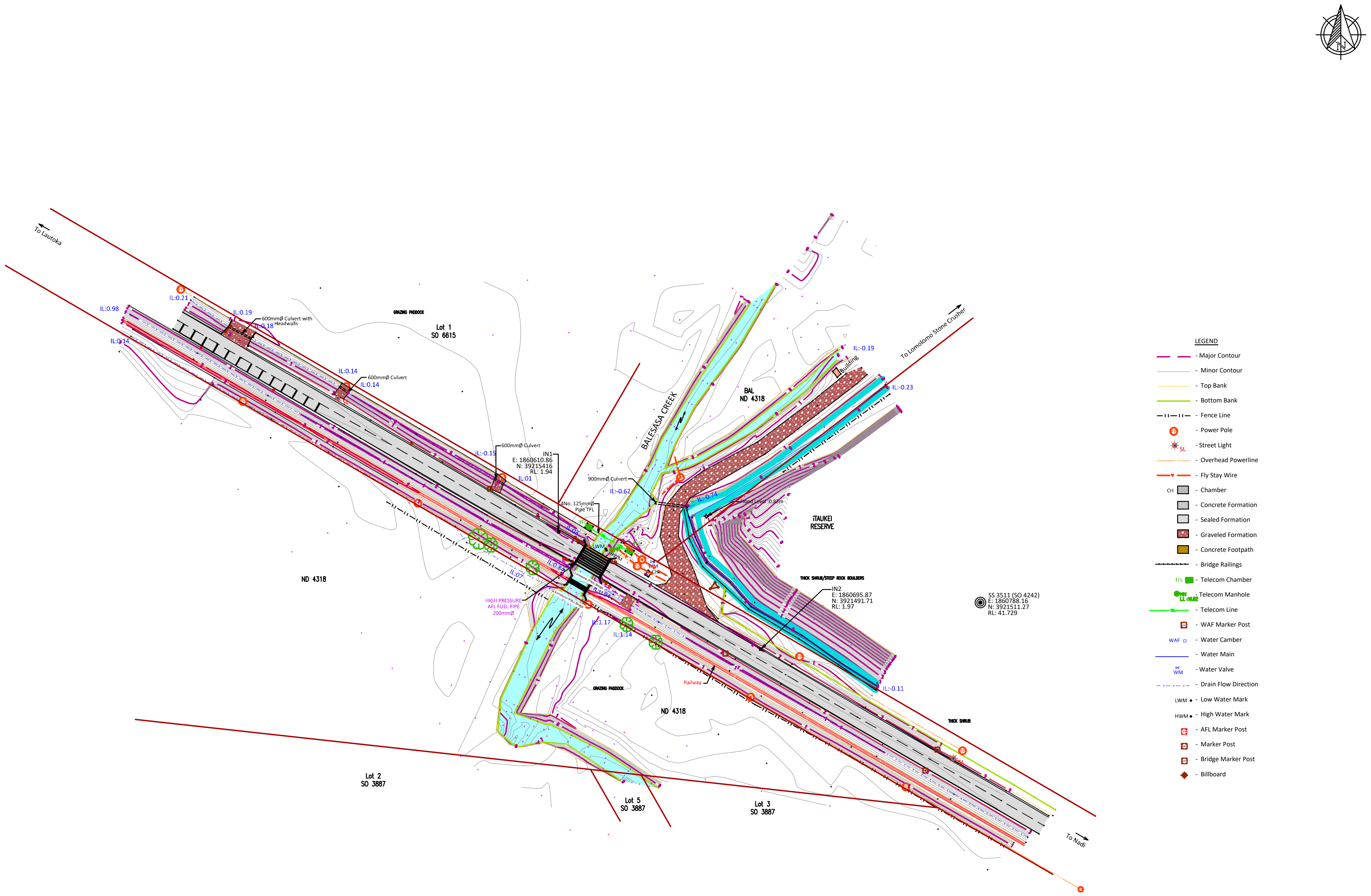
email: shiri.narayan@fijiroads.org

DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF SABETO BRIDGE

TIKINA: SABETO   PROVINCE: BA   ISLAND: VITI LEVU

REQUEST FROM:	BRIDGE & STRUCTURES
DATE OF REQUEST	19/01/2022
Scales	1:1000 @ A1
Drawing No.	FRA: SS 25/22
Rev.	0



NOTES:

1. DATUM OF LEVELS : MEAN SEA LEVEL
   ORIGIN OF LEVELS: SS 3511 (SO 4242)
   RL: 41.729m
2. DATUM OF COORDINATES : FIJI MAP GRID
   ORIGIN OF COORDINATES: SS 3511 (SO 4242)
   E: 1860788.16
   N: 3921511.27
3. CONTOUR INTERVALS: MAJOR: 1m
   MINOR: 0.20m
4. THIS PLAN DOES NOT NECESSARILY SHOW ALL EXISTING SERVICES. IT'S THE DUTY OF THE CONTRACTOR TO ACCURATELY LOCATE AND PROTECT ALL EXISTING SERVICES BEFORE ANY EXCAVATION.
5. ALL DIMENSIONS, LEVELS & UNDERGROUND SERVICES LOCATIONS TO BE CHECKED ON SITE PRIOR TO COMMENCEMENT OF ALL WORKS.
6. ALL DIMENSIONS ARE IN METERS.
7. LOW WATER MARK : -0.56m
   HIGH WATER MARK : -0.02m
8. SOFFIT LEVEL : FRA BRIDGE (LOMOLOMO) : 1.03m
   FSC BRIDGE (LOMOLOMO) : 1.18m
9. FLOOD LEVEL - Reduced Level : 0.83m

REV	REVISIONS	DRN	CHK	APP	DATE

SURVEYED BY	KRISHNEEL LAL
SURVEY ASST	TOMASI KORORUA & VILIAME ANTONIO
DRAWN BY	USAIA DELAI
CHECKED BY	SHIRI NARAYAN
VERIFIED BY	SHAINEEL CHAND
SURVEY INSTRUCTION	(SI) No.SS 24/22
DATE OF SURVEY	02/03/2022
APPROVED	SHIRI NARAYAN
SURVEY SECTION	

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DESCRIPTION:

DETAILED TOPOGRAPHICAL SURVEY OF LOMOLOMO BRIDGE

TIKINA: VUDA PROVINCE: BA ISLAND: VITI LEVU

REQUEST FROM:	BRIDGES & STRUCTURES
DATE OF REQUEST	13/12/2021
Scales	1:1000 @ A1
Drawing No.	FRA: SS 24/22
Rev.	0

B

Appendix B – Flood Modelling Report

Beca

Fiji 40 Bridges - P1 Hydrology and Flood Modelling

Priority 1 Bridges

Prepared for Fiji Roads Authority

Prepared by Beca International Consultants Ltd

27 March 2024

Creative people together transforming our world

Sensitivity: General

Revision History

Revision Nº	Prepared By	Description	Date
A	Monica Hoetjes and Hans Ching	Draft for Concept Design	7/02/2023
B	Monica Hoetjes and Hans Ching	Detailed Design	27/03/2024

Document Acceptance

Action	Name	Signed	Date
Prepared by	Monica Hoetjes and Hans Ching		27/03/2024
Reviewed by	Michael Law and Cameron Oliver		27/03/2024
Approved by	Craig Hatley		27/03/2024
on behalf of	Beca International Consultants Ltd		

Contents

Appendices

Executive Summary

This report describes the hydrological and hydraulic modelling used to inform the design of the ten Priority 1 bridges.

Flood flows have been calculated using the SCS loss and unit hydrograph methods for the SLS2 and ULS design events defined in the NZTA Bridge Manual (NZBM 2018). These design flows provided upstream boundary conditions for 2D HEC-RAS models developed for each bridge. The model geometry is based on local photogrammetry and topographical surveys. Where bridges are affected by tides and extreme sea levels, these have been used as the downstream boundaries of the models. Increases in rainfall and sea level due to climate change have been included in the modelling.

Table 0-1 shows the modelled design flood levels for the Priority 1 100% Detailed Design bridges and (where required) temporary bridges.

Table 0-1. 100% Detailed Design Priority 1 modelled design flood levels.

Bridge		Island	Bridge importance level	Tidally dominated in flood events	Design flood level at 100% Detailed Design (mRL)				Bank velocity (m/s)
					SLS2	ULS	Temp SLS2	Temp ULS	
1	Medraukutu	Viti Levu	3	Yes	2.5	3.0			1.8
2	Lami	Viti Levu	3	No	2.8	3.2			4.8
3	Navutu	Viti Levu	3	Yes	4.0	5.0			2.8
4	Vunitogoloa	Viti Levu	3	Yes	4.0	4.8	3.5	3.9	1.7
5	Viseisei	Viti Levu	3	Yes	3.1	4.2			1.8
6	Vitawa	Viti Levu	3	Yes	4.7	5.8	3.9	5.3	3.4
7	Navola	Viti Levu	3	No	3.6	3.9			1.1
8	Matawalu	Viti Levu	3	No	4.3	4.7	3.3	3.9	3.2
9	Sabeto	Viti Levu	3	No	3.8	4.2			4.3
10	Lomolomo	Viti Levu	3	Yes	3.2	4.1			2.1

Summary sheets have been provided for each bridge showing:

- Bridge location
- Existing bridge topography, aerial photograph, oblique photograph, and modelled bridge representation
- Design and temporary bridge topographies and model representations
- Tabulated peak flood levels, water velocities and water depths for modelled scenarios.

1 Introduction

This report describes the flood modelling undertaken to inform the design of the ten Priority 1 (P1) bridges, all of which are located on Viti Levu. The modelling informs design bridge levels and the design of erosion protection to the bridges and river banks.

1.1 Bridge Locations

The Priority 1 bridge locations are shown in Table 1-1 and Figure 1-1, with short summaries of each crossing provided below. All of these bridges at located at, or near the coast. During the SLS2 and ULS design flood events, peak flood levels can be dominated by sea level, river flood flows or a combination of the two.

Table 1-1: Bridge Locations

Number	Bridge Name	Island	Importance Level	Tidally dominated in flood events	Existing bridge layout
1	Medraukutu	Viti Levu	3	Yes	Multi-span bridge on the coast
2	Lami	Viti Levu	3	No	Multi-span bridge on the coast
3	Navutu	Viti Levu	3	Yes	Multi-span bridge close to the coast
4	Vunitogoloa	Viti Levu	3	Yes	Multi-span bridge on the coast
5	Viseisei	Viti Levu	3	Yes	Multi-span bridge on the coast
6	Vitawa	Viti Levu	3	Yes	Short single span bridge on the coast
7	Navola	Viti Levu	3	No	Short single span bridge on the coast
8	Matawalu	Viti Levu	3	No	Multi-span bridge inland
9	Sabeto	Viti Levu	3	No	Multi-span bridge inland
10	Lomolomo	Viti Levu	3	Yes	Short single span bridge inland

Figure 1-1 Priority 1 Bridge Location Map

1.1.1 Medraukutu

Situated on the Queens Road west of Suva, the existing bridge is arched and higher than the road approaches. The bridge is on the coast and so flood levels are dominated by extreme sea levels, though exacerbated by runoff from the upstream catchment. Upstream of the bridge, there are dense mangroves in the creek, and mangroves cover the banks of the bay downstream of the bridge. On the upstream western bank, houses are sited on ground that is lower than the road level.

Figure 1-2: Medraukutu Bridge

1.1.2 Lami

The Lami Bridge is on the coast west of Suva. There is a confluence of two streams and a wider tidal basin just upstream of the existing bridge. The banks of the tidal basin are covered with mangroves, while the banks around the bridge are protected by rocks, gabions and filled tyres downstream. The existing bridge road level is higher than the road approaches and surrounding land, which is developed for a mixture of commercial, light industrial, recreational, and residential uses. Hydraulic modelling of the SLS2 and ULS flood events has shown that river catchment flow dominates peak flood levels, even though the bridge is located at the coast.

Figure 1-3: Lami Bridge

1.1.3 Navutu

The Navutu bridge is located approximately 350 m from the northwest coast of Viti Levu, in Lautoka. There is a rail bridge on the downstream side of the existing bridge. The banks of the river channel are steep and heavily vegetated, and the bridge structures trap debris. Peak flood levels at this site are influenced by tidal levels.

Figure 1-4: Navutu Bridge

1.1.4 Vunitogoloa

The current bridge is very low-lying, with the current bridge deck less than 2 m above the bed of the river. The bridge is subject to flooding and will trap debris. The site is less than 1 km from the north coast of Viti Levu and is on the boundary of where peak flood levels are affected by high sea levels or river flows. The village lies on the true right (east) bank of the river, and so tie-ins to local roads, houses, and village amenities limit the amount that the bridge can be raised.

Figure 1-5: Vunitogoloa Bridge

1.1.5 Viseisei

The Viseisei bridge is positioned across the large Vuda River on the west coast of Viti Levu, approximately 650 m upstream of the coast. The site is flat, tidally influenced, and mangroves occupy the riverbanks in the area around the bridge. Peak flood levels at this site are influenced by tidal levels. The Viseisei floodplain is located north of the Lomolomo bridge floodplain. There is a rail bridge 10 m downstream of the existing bridge. Utility pipes attached to the existing bridge mean that it will remain, and tie-ins to local roads limit the ability to raise the new bridge.

Figure 1-6: Viseisei Bridge

1.1.6 Vitawa

This bridge is about 500 m from the north coast of Viti Levu where the road crosses the floodplain. The road is at grade, and floodwater will cross the road and existing bridge deck. The existing bridge soffit is less than 2 m above normal water level. Large debris can be conveyed by the river and gets stuck under the bridge.

Figure 1-7: Vitawa Bridge

1.1.7 Navola

Navola bridge is located across Komave Creek, immediately westwards of Navola Village on the southern coast of Viti Levu. The bridge is located 90 m inland from the coast and is tidally influenced under normal river flow conditions. Under high flow river conditions, flood levels are not tidally dominated. The site is generally flat on the western side of the bridge, but there is a steep hill on the eastern side of the bridge which prevents floodwater from spilling eastwards. The proposed bridge is to be positioned immediately upstream of the existing bridge. The proposed bridge is to be lifted above the SLS2 and ULS flood events, to reduce the amount of rock cutting required, and reduce the flood forces, debris accumulation and obstruction of the skewed bridge piers.

Figure 1-8: Navola Bridge

1.1.8 Matawalu

The bridge at Matawalu crosses the river in a meandering section of the river close to the northern edge of a wide floodplain, which means there is potential for flows to bypass the small modelled area. The river is close to the coast and is tidally affected under normal river flow conditions. A meander of the river downstream brings the channel back to near the bridge site. The horizontal alignment of the bridge and approaches is curved. A temporary bridge will be built upstream.

Figure 1-9: Matawalu Bridge

1.1.9 Sabeto

The Sabeto bridge crosses the large Sabeto River, with an upstream catchment area of approximately 90 km^2. The Sabeto floodplain is adjacent to the Lomolomo floodplain. Only a small portion of the Sabeto floodplain has been modelled due to survey availability. A portion of the modelled flow is expected to bypass the modelled extent. If the entire upstream catchment flow were applied to the narrow model extent, there is the potential to over-estimate flood levels.

Figure 1-10: Sabeto Bridge

1.1.10 Lomolomo

This site is very low-lying, located only 1.2 km inland eastwards from the coast. The channel is small and artificially aligned, with flood gates 1.1 km downstream. There is a rail bridge downstream of the existing bridge, and the existing bridge will be retained because of an attached oil pipe, with the new bridge located just upstream. The Lomolomo bridge catchment floodplain is located between the Viseisei and Sabeto floodplains.

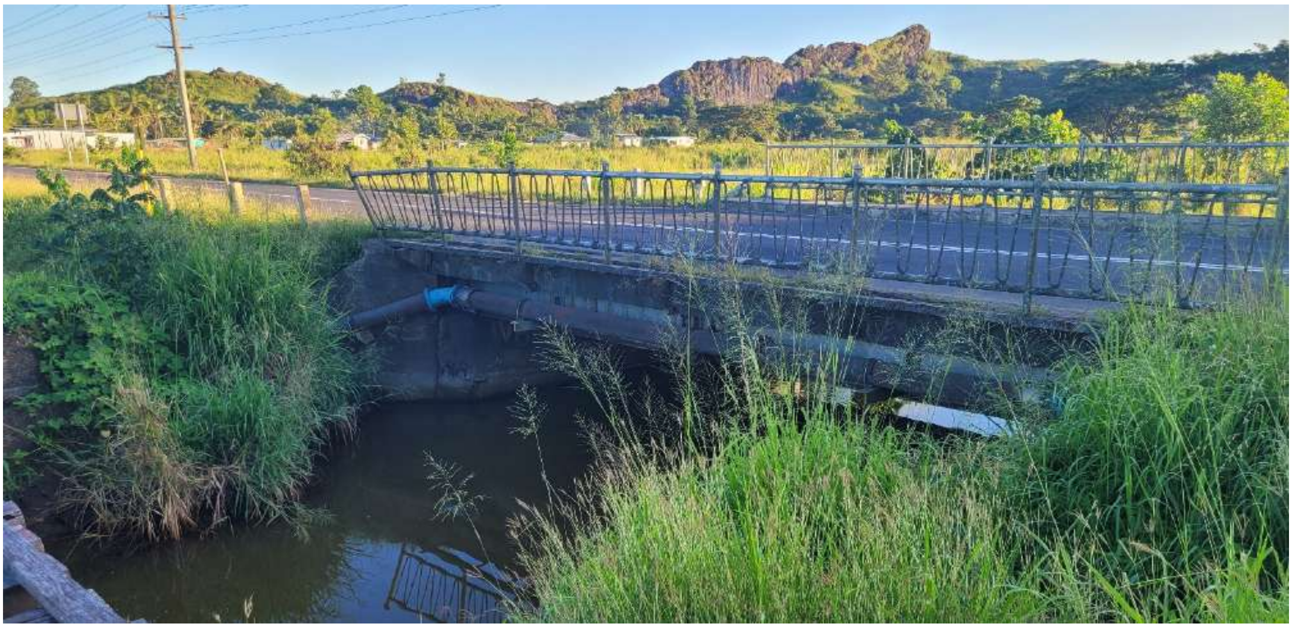

Figure 1-11: Lomolomo Bridge

1.2 Design Criteria

The design criteria for the project are laid down in the document ***Design Criteria – Bridges Priority 1. FRA 20/13: 40 Critical bridges & 3 Maritime Structures*** (Beca 2022). Regarding mitigation of flood risk, the relevant parts of the design criteria are reproduced in Table 1-2.

Table 1-2: Design Criteria for Hydrology and Flood Modelling

No.	Item	Details
Design Manuals and Standards		
1.	Primary Design Codes, Bridge Design	New Zealand Bridge Manual, 3rd edition, Amendment 3, October 2018, (NZBM 2018)
3. General Requirements		
1.	Design Life	The design life of all primary structural bridge elements will be 100 years in accordance with FRA (Fiji Roads Authority) DG (Design Guide)
3.	Bridge Plan Position	The position of each new bridge will be confirmed after geotechnical, topographical, and hydraulic assessments are completed and replacement alignment options are developed and evaluated during the Options Assessment Phase. The permanent and temporary bridges will be positioned to mitigate environmental and social impacts where possible, to facilitate safe and adequate access during construction stage, and provide a cost-effective solution.
7.	Bridge Vertical Alignment & Soffit Level	The bridge soffit will be set above the higher of: ULS flood event +0.6m debris load clearance as per AS5100.2*1, Section 16.6.3 (except where bridge superstructure can resist debris load) SLS2 flood event + 0.6m*2 or 1.2m*2 freeboard as per NZ Bridge Manual Notes: *1 NZ BM refers to AS5100.2 for debris load parameters. *2 0.6m normal circumstances, 1.2m where there is possibility that large trees may be carried down the waterway The Average Recurrence Interval (ARI) of the design flood event (SLS2 / ULS flood) will be derived from NZ Bridge Manual, Table 2.1, for the Importance Level of the bridge and section 2.3.2 Design floods, Item (b). This specifies that the total waterway shall be designed to pass the ARI flood corresponding to SLS2 flood. Rainfall for the design storm (e.g. 100-year ARI for SLS2 for Importance Level 3 bridges) of critical duration for the upstream catchment will be used to derive the design flood hydrograph. Design rainfall depth-duration-frequency tables (used to derive flood hydrographs) will be developed from rainfall information provided by Fiji Meteorological Service for the closest rain gauges to the bridge locations. Where bridges are also subject to tidal water levels, the design flood levels will be taken as the maximum modelled water level from two model runs: SLS2 design flow with 20-year ARI extreme sea level, and 20-year ARI flow with SLS2 design event sea level. Extreme sea levels will be taken from the Climate Risk and Vulnerability Assessment (CRVA) report (Beca 2024), and with reference to the Design Criteria for Maritime Structures (Beca 2022). The effects of climate change are defined in Item 8 below. It is expected that the existing road level and waterway opening are maintained or increased.

No.	Item	Details
8	Climate Change - Sea Level Rise and Rainfall Intensity	Sea Level Rise The sea level rise requirement is based on the latest IPCC AR6 climate change guidance (IPCC 2021). The sea level rise allowance was discussed with FRA and it was agreed that the design should adopt (for details refer NTCs 105 and 149): Reference / base design – 0.73m (derived from SSP1-2.6 emission scenario) Sensitivity assessment – 1.09m (derived using SSP3-7.0 emission scenario) Rainfall Intensity Increase Reference / base design – 10% (using SSP1-2.6 emission scenario agreed for SLR) Sensitivity assessment – 40% (using SSP3-7.0 emission scenario agreed for SLR) For the bridge design, the increases were estimated based on the methodology described in Accounting for Changes in Extreme Daily Rainfall Intensity in Pacific Island Countries (ADB, December 2021)
19.	Scour and Erosion Protection	Subject to conclusions of hydraulic or wave assessment and site-specific details, river banks at bridge abutments or approach formations exposed to waves will be provided with rock armour protection (or similar structure) to reduce the risk of scour and erosion.
6. Bridge Design Loading		
5.	Waterway Actions	Flood water actions on piers and other bridge elements will be determined as per AS5100.2:2017, Section 16 Forces Resulting from Water Flow.
7. Temporary Bridges / Crossings during Construction		
3.	Bridge Vertical Alignment & Soffit Level	Vertical alignment will be selected to minimise earthworks. The bridge soffit will be set above the higher of: ULS event +0.6m debris load clearance as per AS5100.2, Section 16.6.3 SLS1 event + 0.6m or 1.2m freeboard Notes: NZ Bridge Manual refers to AS5100.2 for debris load parameters. 0.6m normal circumstances, 1.2m where there is possibility that large trees may be carried down the waterway exists A reduced storm event can be used, subject to acceptance from FRA, for design of temporary pipe culvert type crossings. A 10-year ARI storm hydrograph is suggested for the design of temporary works, rather than the 100-year ARI storm used for permanent works. This reflects the reduced risk of a significant storm event occurring during the life span of temporary works. The effects of climate change do not need to be accounted for in the design of temporary/construction works.
6.	Bridge Importance Level	Matching importance of the corresponding permanent bridge.

Key points:

- The Waka Kotahi NZTA Bridge Manual is the main document for setting the criteria for bridge clearance above modelled flood levels. As noted later in the report, these criteria were relaxed for some bridges to accommodate other local requirements.

- Where possible, the bridges have been sized and located to "mitigate environmental and social impacts" and "provide a cost-effective solution".
- Climate change has been accounted for in the design of the permanent bridges.
- The outputs of the flood modelling are an input to the scour protection design.

1.3 Modelling Approach

Our approach to the hydrological and hydraulic modelling has been to:

- Provide robust estimates of flood levels, flood extents and water velocities to inform the level and design of the proposed bridges, while recognising the limited availability of survey and hydrological information, and hence uncertainty in the model results.
- Use freely available software, GIS data and hydrometric information. To achieve this, we have used:
- HEC-HMS1 and HEC-RAS2 hydrological and hydraulic modelling software, developed by the US Army Corps of Engineers and widely used worldwide.
- Global GIS data sets including:
- 30 m grid DEM (digital elevation model)
- Vegetation/land-use and soils

To achieve this, the modelling comprised the following tasks:

1. Define the catchment draining to each bridge using available world-wide DEM 30m grid topographical data, cross-checking against available aerial imagery and site visits.
2. Undertake hydrological modelling using HEC-HMS with appropriate loss and unit hydrograph methods and rainfall inputs derived from Fiji Meteorological Service extreme event rainfall to generate peak flow hydrographs for the design events. Potential effects of climate change and tidal levels over the lifetime of the bridge are also incorporated.
3. Develop hydraulic models using Global Mapper/QGIS and HEC-RAS to calculate design flood water levels and velocities. *Note that site-specific information, including detailed and floodplain-wide elevation data, is limited for the majority of sites.*
4. Liaise with bridge designers and test bridge design options to confirm freeboard requirements, flood extents, and predicted scour depths.

1.4 Design Events

The design events for the flood modelling, and hence design rainfall, are based on Table 2.1 and Section 2.3 of the New Zealand Bridge Manual, 3rd Edition, Amendment 3, October 2018 (NZBM), as set out in the Design Criteria report (Beca 2022).

The NZBM states that the bridge shall be designed to the ultimate limit state (ULS) and serviceability limit state (SLS) events based on the Importance Level of the bridge as per AS/NZS 1170.0. ULS is the state beyond which the strength or ductility capacity of the structure is exceeded, or when it cannot maintain equilibrium and becomes unstable, whereas SLS is the state beyond which the structure becomes unfit for its intended use due to deformation, vibratory response, degradation, or other operational inadequacy.

[1] https://www.hec.usace.army.mil/software/hec-hms/

[2] https://www.hec.usace.army.mil/software/hec-ras/

Many of the bridges are located on (or close to) the coast and so are tidally affected. Section 2.5 explains the combinations of river flow event and storm tide levels used to model the SLS and ULS design events. The full list of model scenarios is shown in Section 2.6.

Table 1-3 below is a summary of the ULS and SLS design events based on the Importance Level of the bridge. Design events are expressed as an average recurrence interval (ARI) in years.

Many of the bridges are located on (or close to) the coast and so are tidally affected. Section 2.5 explains the combinations of river flow event and storm tide levels used to model the SLS and ULS design events. The full list of model scenarios is shown in Section 2.6.

Table 1-3: SLS and ULS design events

Importance Level (as per AS/NZS 1170.0)	Bridge Permanence	ARI (years) for Floodwater Actions	
		Serviceability Limit State (SLS)	Ultimate Limit State (ULS)
2	Temporary	25 (SLS1)	250
	Permanent	50 (SLS2)	500
3	Temporary	25 (SLS1)	500
	Permanent	100 (SLS2)	1000

Table 2.1 of the Bridge Manual doesn't provide a SLS 2 design event for temporary bridges, and so the 25-year ARI SLS1 event has been selected as providing a balanced risk for the temporary bridges.

All of the Priority 1 bridges are Importance Level 3.

1.5 Report Structure

Section 2 of the report describes the hydrological modelling used to define the design flow hydrographs that are used as the upstream boundary conditions for the hydraulic flood modelling, which is described in Section 3.

The hydrological modelling described in Section 2 includes:

- The estimation of design rainfall hyetographs.
- Catchment definition.
- Rainfall losses and rainfall-runoff transformation.
- Summary of catchment parameters and calculated peak design flows.
- Extreme sea levels, along with the combinations of river flow and tide to be modelled.
- As noted above, the full list of scenarios to be modelled are listed in Section 2.6.

The hydraulic flood modelling described in Section 3 includes:

- Confirming the modelling approach and software.
- Model geometry, including model extents, structures and boundary conditions.
- Model scenarios and equation set.
- Results
- Design levels for each bridge.
- Short commentaries for each bridge.

Section 4 describes the review and verification process for the modelling.

2 Hydrological Modelling

2.1 Rainfall

Robust sub-daily rainfall depth/intensity-duration-frequency data is limited in Fiji, and so we used a combination of daily and sub-daily data to create depth-duration-frequency (DDF) rainfall tables for each of the forty bridges and three jetty sites. Fiji Meteorological Service (FMS) provided us with information sheets for the 24-hour frequency for multiple sites across the country (FMS 2021), and sub-daily DDF tables for Nadi Airport (FMS, 2007a), Laucala Bay (Suva) (FMS, 2007b), and previously for Labasa Airport (FMS, 2019), as shown in Figure 2-1. We also have a GIS layer of annual rainfall across Fiji. Based on this information, our method for estimating the design rainfall for each bridge catchment or jetty site was to:

1) Create a sub-daily DDF for the closest raingauge to the bridge catchment or jetty.
   a) Identify the closest raingauges with 24-hour DDF and the nearest of the three raingauges with sub-daily DDF data.
   b) Factor the 24-hour DDF totals by the chosen sub-day DDF raingauge data.
2) Create a sub-daily DDF for the bridge catchment or jetty site.
   a) Use the map of annual rainfall to calculate the ratio of rainfall at the site divided by the rainfall at the rain gauge (the rainfall factor).
   b) Apply this rainfall factor to the sub-daily DDF for the closest raingauge to the bridge catchment or jetty.

Figure 2-1 Rainfall DDF Sites

For example, to create the sub-daily DDF for Vunitogoloa Bridge, we used the following inputs:

- Nearest 24-hour DDF site: Penang Mill

- Nearest sub-daily DDF site: Nadi
- Annual rainfall at Vunitogoloa: 2,624 mm
- Annual rainfall at Penang Mill: 2,622 mm

From this, we created a sub-daily DDF for Penang Mill by factoring the 24-hour DDF by the sub-daily distribution in the Nadi DDF. We then multiplied the rainfall depths in the resulting table by the annual rainfall factor of 1.001 (2624/2622) (Table 2-1) to create the site-specific sub-daily DDF (100-year ARI shown in Figure 2-2).

We used the site-specific sub-daily DDF tables to develop a 24-hr nested storm profile (hyetograph) at each site. We scaled the nested storm rainfall profiles up by an additional 10% and 40% to allow for an increase in rainfall intensity over time due to climate change, based on Section 6.3.2 of FRA (2019). The 10% increase is used for design, while the 40% increase is used to test the sensitivity of the design.

Table 2-1: Rain Gauge and Scaling Applied at Each Bridge

Bridge		Nearest Rain Gauge	Sub-daily Distribution	Catchment Rainfall Factor	100-year ARI 24-hour 'Historic' Rainfall (mm)
1	Medraukutu	Laucala Bay	Suva (Laucala Bay)	1.003	409
2	Lami	Laucala Bay	Suva (Laucala Bay)	1.003	409
3	Navutu	Lautoka Mill	Nadi	1.000	367
4	Vunitogoloa	Penang Mill	Nadi	1.001	511
5	Viseisei	Nadi Airport	Nadi	1.004	371
6	Vitawa	Penang Mill	Nadi	1.000	511
7	Navola	Tokotoko (Navua)	Suva (Laucala Bay)	0.905	330
8	Matawalu	Lautoka Mill	Nadi	1.017	373
9	Sabeto	Nadi Airport	Nadi	1.025	378
10	Lomolomo	Nadi Airport	Nadi	0.997	368

Project site	VUNITOGOLOA BRIDGE	
Rain gauge	**Penang Mill**	
Storm profile	**Nadi**	
Event (ARI)	100	year
Historic 24 hr rainfall depth	511	mm
Scaling factor	1.00	

Design event rainfall depths

ARI (years)	10min	20min	30min	60min	2 hrs	6 hrs	12 hrs	24 hrs
100	53.1	93.6	117.5	164.4	204.3	332.4	434.7	511.4
100+10%	58.4	102.9	129.3	180.9	224.8	365.6	478.1	562.5
100+40%	74.4	131.0	164.5	230.2	286.1	465.4	608.6	715.9

Figure 2-2: Vunitogoloa Bridge Catchment Design Rainfall Depths

2.2 Catchment Definition

The catchment areas (Figure 2-4) contributing to each bridge were defined using the SRTM Worldwide Elevation Data (NASA JPL, 2013) (1 arc-second resolution, approximately 30 m) shown in Figure 2-3, and checked against aerial photographs and Google Earth. Definition of the area and longest drainage path for catchments with smaller streams and wide floodplains were more difficult than for the larger catchments, and so were checked using local sources and aerial photographs. Figure 2-4 shows the catchments upstream of each bridge.

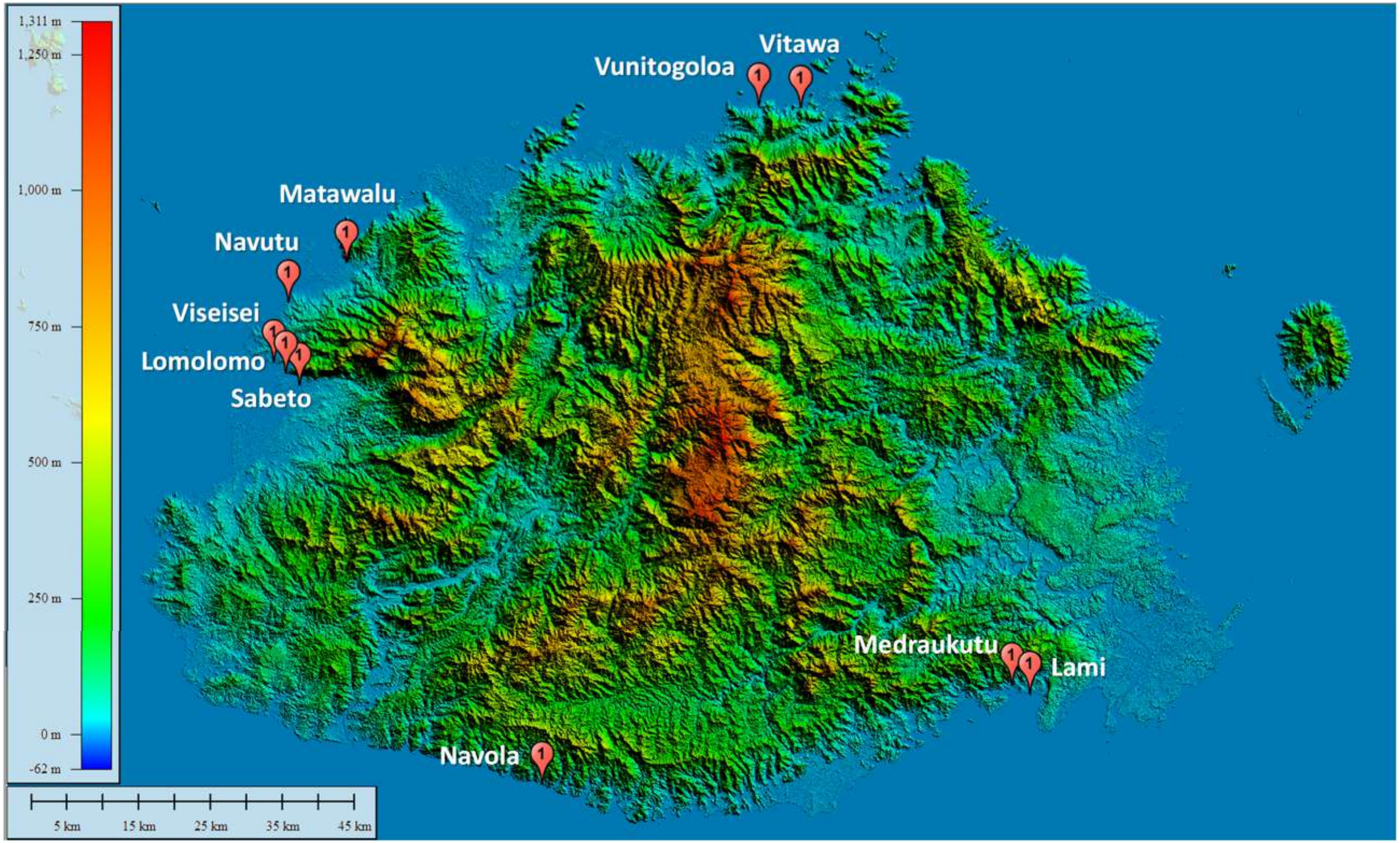

Figure 2-3: SRTM Worldwide Elevation Data and P1 Bridge Locations

Figure 2-4: Catchment Boundaries

2.3 Rainfall Losses and Rainfall-Runoff Transformation

For hydrological modelling, catchment parameters describing the land use, runoff characteristics, and catchment length and slope are required. We estimated the flow in each waterway, for a range of return periods, using the US Soil Conservation Service SCS curve number and unit hydrograph methods.

2.3.1 Rainfall Losses

During a rainfall event, a portion of the rainfall will be intercepted by vegetation, become trapped in depressions or infiltrate into the soil. These rainfall losses are accounted for in hydrological modelling. We used HEC-HMS for the hydrological modelling for this project, to estimate the transformation from rainfall to the river flow at each bridge site. The loss method we selected was the SCS curve number method. HEC-HMS requires the SCS curve number, initial abstraction, and impervious catchment as inputs.

The curve number is a measure of the infiltration capacity of a soil, and it is dependent on the land cover and soil type/group. We used a global land cover classification data set to define catchment land cover (Friedl and Sulla-Menashe, 2019). We chose this specific classification data set because it is designed for use in surface hydrology. Using GIS spatial analysis, we calculated the percentage coverage of each land cover type across each catchment.

We used a global soil group map to define the hydrologic soil group for each catchment (Ross et al., 2018). Hydrologic soil groups represent the runoff potential of a soil, and hydrologic soil groups A, B, C and D correspond to low, moderately low, moderately high, and high runoff potential respectively. Using GIS spatial analysis, we calculated the percentage coverage of each soil group across each catchment. From these maps, the hydrologic soil groups within our catchments were hydrologic soil group C, D, or a dual hydrologic soil group C/D. If a soil is assigned the dual hydrologic soil group C/D, this means that the soil is hydrologic soil group C if the soil is well drained, and hydrologic soil group D if the soil is undrained. Where an area had been assigned hydrologic soil group C/D, we assumed that 50% of that area is well-drained and hydrologic soil group C, and that the other 50% of the area is poorly-drained and hydrologic soil group D. We made this assumption in the absence of other information to inform catchment drainage.

Once we had an estimate of land cover and soil group across each catchment, we assigned a SCS curve number to each land cover, for each hydrologic soil group (Table 2-2). We chose the SCS curve numbers that best related to the land cover, from Table 2-2 of Technical Release 55, Urban Hydrology for Small Watersheds (NRCS, 1986).

Table 2-2. Land Cover and Soil Group Curve Numbers

Land Cover	SCS Curve Number	
	Hydrologic Soil Group C	Hydrologic Soil Group D
Water bodies	100	100
Dense forests	70	77
Open forests	73	79
Grasslands	74	80
Woody wetland	86	86
Herbaceous wetland	80	80
Impervious area	98	98

Once we had assigned SCS curve numbers to each land cover, we then calculated the curve number for each bridge catchment. To do so, we calculated the area-weighted average of the curve numbers assigned to the land cover types that were present in each catchment (Table 2-3).

The SCS curve number method in HEC-HMS also requires the percentage of impervious area and the initial abstraction depth as inputs. We calculated the initial abstraction depth from the curve number, and this accounts for all losses prior to runoff e.g., infiltration, evaporation.

Table 2-3: Curve Numbers and Loss Parameters

	Bridge site	Curve number	Initial abstraction (mm)	Impervious area estimate (%)
1	Medraukutu	77.6	14.7	4
2	Lami	78.0	14.4	4
3	Navutu	83.7	9.9	30
4	Vunitogoloa	78.8	13.7	<1
5	Viseisei	78.0	14.3	1
6	Vitawa	78.9	13.6	<1
7	Navola	75.0	16.9	1
8	Matawalu	78.8	13.7	1
9	Sabeto	77.1	15.1	<1
10	Lomolomo	81.4	11.6	25

2.3.2 Rainfall-Runoff Transformation

We selected the SCS unit hydrograph method as our transform method in HEC-HMS. This method requires 'lag time' as an input. Lag time is defined as the difference between the centre of mass of excess rainfall and the peak runoff rate. Lag time is defined as 2/3 of the time of concentration of the catchment. The time of concentration is the time needed for water to flow from the most remote point in the catchment to the bridge site. We calculated the Tc for each site using the Bransby-William equation, which uses the catchment area, longest drainage path and average slope (Table 2-4).

Table 2-4: Catchment Parameters, Time of Concentration and Lag Time

Bridge site		Area	Longest drainage path (Length)	Slope	Time of concentration (Tc)	SCS lag time ($^2/_3$Tc)
		km²	*km*	*%*	*hrs*	*mins*
1	Medraukutu	5.52	2.30	5.6	0.84	34
2	Lami	20.75	2.53	12.4	0.69	28
3	Navutu	3.80	3.65	1.6	1.79	72
4	Vunitogoloa	8.91	5.29	1.4	2.44	98
5	Viseisei	57.85	20.51	2.3	7.12	285
6	Vitawa	3.67	3.82	3.6	1.60	64
7	Navola	4.35	4.20	5.1	1.61	64
8	Matawalu	69.65	19.91	0.9	8.18	327
9	Sabeto	88.87	23.82	1.2	9.02	361
10	Lomolomo	3.60	1.80	24.4	0.51	21

2.4 Design Flows and Hydrographs

Table 2-5 show the resulting peak flows for each bridge catchment from HEC-HMS. These flows are the peak value of flow time series (flow hydrographs). These flow hydrographs were used as the upstream flow boundaries in the HEC-RAS hydraulic models.

Table 2-5: Catchment Peak Flows (m^3/s)

	Bridge	10y*	25-year ARI			100-year ARI			500y*	1,000-year ARI		
			No CC	10% CC	40% CC	No CC	10% CC	40% CC		No CC	10% CC	40% CC
1	Medraukutu	-	134	150	196	171	191	248	-	233	258	334
2	Lami	-	539	601	787	687	764	993	-	933	1033	1333
3	Navutu	-	61	68	88	78	86	111	-	106	117	150
4	Vunitogoloa	124	159	177	231	209	232	301	268	293	324	417
5	Viseisei	-	371	417	555	493	552	727	-	698	777	1012
6	Vitawa	66	84	94	122	111	123	159	142	155	171	220
7	Navola	-	59	67	90	76	85	113	-	103	115	151
8	Matawalu	336	423	475	631	554	619	814	707	773	860	1120
9	Sabeto	-	495	557	745	661	740	977	-	938	1045	1365
10	Lomolomo	-	102	114	147	132	146	189	-	182	201	258

* Flows only applicable to sites with temporary bridges

2.5 Accounting for Tides, Sea Level Rise and Storm Surge

All of the Priority 1 bridges are either located on the coast or near the coast, which means that water levels at these bridges are affected by daily tidal fluctuations high tides, climate change induced sea level rise, or storm surge events. Therefore, we have considered the effect of sea level on the hydraulic performance of these bridges and flooding, as the bridges and any raised approaches or embankments will affect the ability of water to move downstream.

Extreme sea levels were based on information provided in the MetOcean (2022) report for the project.

In our modelling of tidal locations, we have considered the scenario where high river flow events coincide with high downstream tidal levels. While storm surge and extreme rainfall are often generated by the same weather events, it is unlikely that the sea level and rainfall will have the same average recurrence interval (ARI). Therefore, we have adopted the Bay of Plenty Hydrological and Hydraulic Guidelines (2012) to choose which tidal events to combine with which river flows (BoPRC, 2012). For each design event, we have modelled two flow and tide combinations: Case 1 with higher flow and lower tidal levels, and Case 2 with lower flow and higher tidal levels. For the SLS2 and ULS design flood events, our hydraulic modelling has shown whether peak flood levels at each site are dominated by sea level, river flood flows, or a combination of the two.

We have used 20-year ARI sea levels in lieu of 25-year ARI sea levels, as the 25-year ARI sea levels are not available. This small difference is unlike to make a material difference to the hydraulic performance of the bridges.

2.6 Flow and Sea Level Scenarios

Table 2-6 lists the scenarios to be modelled and the design purpose for each scenario.

Table 2-6: Design events for coastally influenced sites

Purpose	Bridge	Rainfall event size	Sea level rise	Flow/tide combination	Flow event for an IL 3 bridge	Tide event for an IL 3 bridge
Setting soffit level	Design	SLS2	0.73m	Case 1	100y + 10%CC	20y + 0.73m SLR
				Case 2	25y + 10%CC	100y + 0.73m SLR
Sensitivity for setting soffit level			1.09m	Case 1	100y +40%CC	20y + 1.09m SLR
				Case 2	25y +40%CC	100y + 1.09m SLR
Erosion protection			N/A	Normal depth	100y +10%CC	Normal depth
Sensitivity for erosion protection				Normal depth	100y +40%CC	Normal depth
Hydraulic loading / setting soffit level		ULS	0.73m	Case 1	1000y +10%CC	100y +0.73m SLR
Setting soffit level				Case 2	100y +10%CC	1000y +0.73m SLR
Sensitivity for hydraulic loading / setting soffit level			1.09m	Case 1	1000y +40% CC	100y +1.09m SLR
Sensitivity for setting soffit level				Case 2	100y +40% CC	1000y +1.09m SLR
Hydraulic loading			0.73m	Normal depth	1000y +10% CC	Normal depth
Sensitivity for hydraulic loading			1.09m	Normal depth	1000y +40% CC	Normal depth
Setting soffit level	Temporary	SLS1	0m	Case 1	25y no CC	10y no SLR
				Case 2	10y no CC	20y no SLR
Erosion protection				Normal depth	25y no CC	Normal depth
Hydraulic loading / setting soffit level		ULS		Case 1	500y no CC	100y no SLR
Setting soffit level				Case 2	100y no CC	500y no SLR

3 Flood Modelling

3.1 Approach and Software

We have developed a hydraulic model for each priority 1 bridge location to inform the bridge design and scour assessments. All of the models were produced in HEC-RAS version 6.2 and 6.3 and developed as 2D flood models. The models include the supplied topographical survey as the model terrain. We also included the flow hydrographs we developed, and the supplied downstream tidal levels as applicable to the scenario. The existing, proposed, and temporary bridge designs were included in separate model geometries.

The survey extents were generally limited, and in many cases did not extend the full width of the floodplain or for any great distance upstream or downstream of the bridge site. Where the survey extents were considered so limited as to result in conservatively high modelled flood levels if the full catchment flow was applied to the bridge area, a low-resolution 30 m grid satellite-derived digital elevation model (DEM) of the full floodplain was used to estimate bypassing floodplain flow, and so refine the design flow through the bridge area.

3.2 Model Geometry

3.2.1 Survey and DEM

Unmanned Aerial Vehicle (UAV) photogrammetry survey and topographical survey was produced for each bridge site. Both the UAV and topographical survey provided a 3D mesh of the ground surface, allowing two digital terrains to be generated for each site. For all sites, the topographical survey was used to generate the hydraulic model terrain. In some cases, the UAV survey was used to increase the modelled terrain floodplain extent. Both the UAV and topographical survey are referenced to Fiji Map Grid 1986 Coordinate System and Fiji Geodetic Height Datum 1986 (mean sea level).

However, the detailed surveyed extents were limited and often did not extend the full width of the floodplain, which could mean that some of the flows calculated in Section 2 would bypass the surveyed model area. Where there was opportunity for bypass of flood flows around bridges, the models were refined using coarse 30m grid DEMs to either extend the detailed bridge model or to estimate bypassing flows using a separate floodplain-wide model, as described in Section 3.2.6.

3.2.2 Land Cover and Roughness

We applied a shapefile land cover layer to the HEC-RAS model to represent various Manning's 'n' roughness across each site. Since a variety of land cover types can be expected at the different bridge sites, we developed a list of typical land cover types found in Fiji with corresponding Manning's 'n' roughness and applied this across our sites (Table 3-1).

Table 3-1 Fiji land cover and Manning's n roughness

Fiji Land Cover Type	Manning's Roughness n
Waterways	
Minimal Vegetation	0.030
Winding, High-Sediment, Some Vegetation	0.045
Heavily Vegetated	0.060
Coastal, Estuary	0.030
Developed Areas	
Roads and Developed Open Areas – Sealed	0.020
Roads and Developed Open Areas – Unsealed	0.025

Fiji Land Cover Type	Manning's Roughness n
Residential Areas – Low Density	0.080
Residential Areas – Medium Density	0.150
Residential Areas – High Density	0.200
Buildings	1.000
Industrial/Commercial – Buildings with Space	0.100
Industrial/Commercial – Cement Works, Quarry	0.120
Vegetation	
Bare Ground – Clay	0.030
Grass – Maintained, Short	0.035
Long Grass and Short Cultivated Crops	0.055
Open Pervious Areas, Moderate Vegetation (Shrubs)	0.070
Sugarcane	0.080
Very Long Grass/Scrub (Waist Height +)	0.100
Mangroves	0.150
Very Dense Scrub/Bush (Palm Tree Height)	0.200

3.2.3 1D/2D models

Each Priority 1 bridge hydraulic model has been developed in 2D due to the presence of wide and flat floodplains, the high likelihood in which the flow path of water can go in multiple directions, the possibility that water levels will vary across the bridge opening, and the availability of the sub-surface bathymetry of the channel in the topographical survey.

All 2D models are grid-based. For the Priority 1 bridges, since the digital terrain extents are relatively small, in general a 3m^2 hexagonal or square grid spacing was applied to both the channel and floodplain to provide greater accuracy and model stability, but without resulting in excessive run times. However, there is some variation between bridges, and tighter grid spacing has generally been applied at structures, as noted below.

3.2.4 Structures

HEC-RAS allows bridges to be modelled in the 2D domain, using the full suite of bridge equations that are used in well-established 1D modelling routines. Using the 2D domain allows flow patterns to be better defined around the bridge piers and abutments.

For each bridge site, we set up an internal 2D area connection along the alignment of the road, and we set up the corresponding bridge at this connection. We applied a tighter 1-2m^2 square grid spacing to the 2D area along the bridge connection.

a. Debris

We have modelled debris on bridge piers based on our assessment of the availability of material in the upstream catchment and the potential for debris to be conveyed to the bridge site. Having noted a bug in the way that HEC-RAS modelled complex bridge piers (those with debris or change of diameter) in 2D, we calculated the effective pier width based on the estimated flood level and the pier geometry including debris. We applied this calculated effective pier width as a constant pier width in the model. This method replicates the reduction of effective flow area in the channel caused by debris, whilst producing more stable model output.

b. Temporary and retained bridges

At some of the bridge sites, the proposed bridge will follow the existing alignment of the road, and so a temporary crossing will be in place during construction of the replacement bridges. At other sites, the new bridge will be on a new alignment. In some cases, the existing bridge will be retained as it carries service pipes that cannot be moved to the new bridge. Table 3-2 lists whether the existing bridges will be retained, the new bridge is on a different alignment, or whether a temporary crossing is required. Where temporary crossings are required, these have been modelled as required by the Design Criteria.

Table 3-2: Bridge Arrangements

Bridge		Existing Bridge Retained	Bridge on New Alignment	Temporary Crossing
1	Medraukutu	No	Yes	No
2	Lami	No	Yes	No
3	Navutu	No	No	No
4	Vunitogoloa	No	No	Yes
5	Viseisei	Yes	Yes	No
6	Vitawa	No	No	Yes
7	Navola	No	Yes	No
8	Matawalu	No	No	Yes
9	Sabeto	Yes	Yes	No
10	Lomolomo	Yes	Yes	No

3.2.5 Boundary Conditions

a. Upstream Boundary

The upstream boundary of the channel for all the models is the design flow hydrograph resulting from HEC-HMS hydrological modelling, as described in Section 2.4.

b. Downstream Boundary

For the downstream boundary of the models, alternative model scenarios were set up to use either a normal depth boundary condition or a fixed water level. The normal depth downstream boundary condition, representing the energy grade or slope of the downstream channel, was applied to represent conditions unaffected by downstream water levels, such as low tide for coastal sites. Alternative model scenarios were also set up to apply fixed water level downstream boundary conditions (stage hydrograph), applied to represent design event sea levels, as described in Section 2.5.

3.2.6 Supplementary Low-definition Floodplain-wide Models

As noted above, the terrains used in the flood models are small due to limited available survey. In many cases, the available survey extents are small in relation to the upstream catchment area and narrow compared to the wider width of the floodplain. Generally, we applied the entire design flow to the upstream boundary of the modelled extents and assumed that all of the design flow is conveyed through the modelled extent and bridge. In reality, this approach ignores the potential for floodwater to be conveyed on the wider, unsurveyed floodplain, and assumes ‘glass-walling’ at the edge of the modelled extent. This can result in an over-estimate of flood levels and scour protection measures, especially where bridges are positioned within wide floodplains.

Where the survey extents were considered so limited as to result in conservatively high modelled flood levels, a low-resolution 30 m grid satellite-derived digital elevation model (DEM) of the full floodplain was used to aid the hydraulic assessment. Two methods were applied:

- In the first method, the 30 m DEM was used to construct a separate 2D hydraulic model to estimate bypassing floodplain flow and so refine the design flow through the bridge area. Due to the poor detailed definition of the 30 m DEM, the river channel was burnt into the DEM based on the dimensions of the channel at the bridge site. This approach was applied to:
  - B8 Matawalu
  - B9 Sabeto
- In the second method, the 30 m grid DEM was used to extend the topographic survey and so increase the extent of the detailed bridge model. The full design flow was passed through the upstream boundary of the extended model. In both methods, the quality of the 30 m grid DEM was insufficient to accurately define the river channel in the extended section of the model, even for the larger rivers, and so representative channels were burnt into the terrain. This approach was applied to:
  - B02 Lami
  - B10 Lomolomo

Refer to Section 3.6 for information on the specific modelling approach applied to each bridge.

3.3 Scenarios

For each bridge site, we have run the scenarios listed in Table 2-6.

3.4 Model Equation Set

HEC-RAS provides a choice of three equation sets to be used for the hydraulic modelling. At Concept design stage, the flood models were run using the Diffusion Wave equation set. This equation set was chosen because it results in more stable models with a quicker model run time when compared to the other equation sets. We also chose this less intensive equation set in keeping with the inherent uncertainty of our other model inputs, such as our limited survey and rainfall information.

In July 2023, our external reviewer (SMEC) requested that we rerun our flood model using the Shallow Water Equations (SWE) equation set. The SWE result in better definition of water levels and velocities through abrupt contractions or expansions, bridges and other hydraulic structures. SWE equations also account for the effects of momentum, which can result in higher water elevations on the outside of bends, such as at B9 Sabeto. Following our external review, we switched to using the original SWE equation set, the SWE-ELM (Eulerian-Lagrangian Method). We also used the newer equation set SWE-EM (Eulerian Method), for sites where we needed a more-momentum conservative equation set to resolve instability in the flood models.

The effect of re-running the models with the SWE-ELM equation set rather than the DW equations was to increase modelled flood levels, generally by 200-300 mm. However, not all of these increases are evident when comparing the 100% Detailed Design modelled flood levels with those reported at Concept Design. This is because there have been other changes to the models, including refinement of the model geometries and updates to the bridge designs.

3.5 Results

Summary model results for individual bridges are presented in Summary Sheets in Appendix A. These were appended to the bridge Design Reports and show:

- Bridge location.
- Existing bridge topography, aerial photograph, oblique photograph, and modelled bridge representation.
  - Design and temporary bridge topographies and model representations.
  - Tabulated peak flood levels, water velocities and water depths for modelled scenarios.

Summary peak water level results for all P1 bridges, as reported at the 100% Detailed Design stage, are shown in Table 3-3.

Table 3-3: Design Flood Level Results

Bridge	Adopted deck level (mRL)		Design flood level at 100% Detailed Design (mRL)				Bank velocity (m/s)
			SLS2	ULS	Temp. SLS2	Temp. ULS	
1	Medraukutu	4.8	2.5	3.0			1.8
2	Lami	5.3	2.8	3.2			4.8
3	Navutu	6.2	4.0	5.0			2.8
4	Vunitogoloa	4.0	4.0	4.8	3.5	3.9	1.7
5	Viseisei	4.7	3.1	4.2			1.8
6	Vitawa	5.8	4.7	5.8	3.9	5.3	3.4
7	Navola	6.1	3.6	3.9			1.1
8	Matawalu	6.7	4.3	4.7	3.3	3.9	3.2
9	Sabeto	6.2	3.8	4.2			4.3
10	Lomolomo	3.5	3.2	4.1			2.1

3.5.1 Agreed Bridge Design Levels

The design criteria define the flood events that are be modelled to inform the proposed the bridge design. To fully meet the design criteria, the bridge deck/road would be raised above the modelled flood level by an allowance for freeboard (to account for debris) plus the thickness of the bridge deck. Generally, freeboard of 1.2 m above the SLS2 flood level and 0.6 m above the ULS flood levels were considered. Bridge superstructures of 1.0 m to 1.2 m were used, depending on the type of bridge spans proposed. The suggested bridge deck levels based on the flood modelling are shown in the third column of Table 3-4.

In some cases, adopting these criteria would raise some of the bridges up to 4 m above the level of the existing bridges and roads. While providing the level of flood resilience required by the design criteria, it is not always feasible to raise bridges by those levels. This may be due to tie-ins with local roads and infrastructure around the bridges, or the bridges crossing small watercourses in floodplains of larger rivers. Each site was discussed with FRA and the BICL design team to agree bridge deck levels (sixth column of Table 3-4) based on the practicalities of raising the bridges.

Note that the SLS2 flood levels reported in the third column of Table 3-4 may differ slightly from those reported at the 'bridge setting' meetings with FRA due to refinements in the modelling and bridge design. However, these changes were communicated and agreed with FRA where they would make a material difference to design considerations.

Table 3-4: Agreed proposed bridge levels

		100% Detailed Design SLS2 flood level		Existing bridge level	Agreed bridge level	Rise in bridge level	Comments
		mRL	Basis	mRL	mRL	m	
1	Medraukutu	2.5	*SLS2 flood level plus 1.2 m freeboard and 1.2 m bridge deck*	4.7	**4.8**	*0.1*	Achieved freeboard and rise in bridge level varies along bridge superstructure elevation (refer to Section 3.6.1). Less than 1.2 m freeboard (1.1 m freeboard) is provided at the western abutment.
2	Lami	2.8	*SLS2 flood level plus 1.2 m freeboard and 1.2 m bridge deck*	4.3	**5.3**	*1.0*	Agreed bridge level meets design criteria for flooding.
3	Navutu	4.0	*SLS2 flood level plus 0.6 m freeboard and 1.2 m bridge deck*	5.3	**6.2**	*0.9*	Lower freeboard agreed to reduce raised approach footprint and minimise effect on adjacent FSC rail bridge/line. Agreed bridge level meets SLS2 design criteria of 0.6 m minimum freeboard. ULS freeboard is not achieved.
4	Vunitogoloa	4.0	*ULS flood level plus 0.6 m freeboard and 1.2 m bridge deck*	2.8	**4.0**	*1.2*	Constrained by village and side road tie-ins on true right (east) bank. The deck is at the same level as the SLS2 flood level, with no freeboard provided in the SLS2 or ULS flood events.
5	Viseisei	3.1	*SLS2 flood level plus 0.6 m freeboard and 1.2 m bridge deck*	2.6	**4.7**	*2.1*	Freeboard allowance relaxed down from 1.2 m to 0.6 m, to allow tie-in with side road on true left (east) bank. Achieved freeboard varies along bridge superstructure elevation.
6	Vitawa	4.7	*SLS2 flood level plus 0.6 m freeboard and 1.2 m bridge deck*	3.5	**5.8**	*2.3*	Agreed bridge level below level based on flood modelling to optimise approaches and tie into local infrastructure
7	Navola	3.6	*SLS2 flood level plus 1.2 m freeboard and 1.2 m bridge deck*	3.7	**6.1**	*2.4*	Agreed bridge level meets design criteria for flooding. Bridge level increased to minimise rock cut as road rises to the east.
8	Matawalu	4.3	*ULS flood level plus 1.2 m freeboard and 1.2 m bridge deck*	5.2	**6.7**	*1.5*	Following sensitivity modelling with revised lower flows, the agreed bridge level was set to meet the SLS2 design criteria of 1.2 m minimum freeboard for debris clearance.
9	Sabeto	3.8	*SLS2 flood level plus 1.2 m freeboard and 1.2 m bridge deck*	4.8 (at abutment)	**6.2**	*1.4*	Agreed bridge level meets design criteria for flooding.
10	Lomolomo	3.2	*SLS2 flood level plus 1.2 m freeboard and 1.2 m bridge deck*	2.3	**3.5**	*1.2*	Agreed bridge level below level based on flood modelling, to reduce rock cutting required and optimise and tie into local infrastructure.

3.6 Bridge Commentaries

Summary sheets are provided for each bridge in Appendix A. These show the modelled bridges and water level and velocity results for the scenarios modelled. Below are brief descriptive summaries for each bridge, which reflects the text in Section 4.3 of the individual bridge detailed Design Reports.

3.6.1 Medraukutu

The Medraukutu bridge superstructure elevation, and achieved freeboard, varies along the bridge length. The lowest point of the deck is at the west abutment, where the deck elevation is 4.8 mRL. The highest point of the bridge deck is at 5.1 mRL, at the centre of the bridge. The bridge structure depth is 1.2 m. Table 3-5 shows the calculated freeboard between modelled flood levels and the bridge soffit.

For the SLS2 river dominated event, the design criteria require a minimum freeboard of 1.2 m to the bridge soffit level at this site. The achieved freeboard in the SLS2 river flow dominated event is greater than 1.2 m for most of the bridge length, but drops to 1.1 m at the western end of the bridge where the deck is lower. The western end of the bridge is away from the main part of the river channel, and so will be subject to lower water velocities and less debris than in the centre of the river.

Table 3-5: Medraukutu Freeboard to Soffit Level

Location	Deck level (mRL)	Soffit level (mRL)	SLS2 1/100 river flow dominated	SLS2 1/100 tide dominated	ULS 1/1000 river flow dominated	ULS 1/1000 tide dominated
			Freeboard to bridge soffit level (m)			
West abutment	4.8	3.6	1.1	1.0	0.8	0.6
Bridge centre	5.1	3.9	1.4	1.3	1.1	0.9

3.6.2 Lami

The Lami hydraulic model geometry is based on local photogrammetry and topographical surveys. Due to the limited survey extent across the Lami Bridge floodplain, the modelled terrain has been extended using a satellite-captured digital elevation model (DEM) with a 30 m grid (Copernicus GLO-30). Though coarse, use of the 30 m DEM improves the representation of how much flow reaches the bridge, and therefore improves the confidence in the flood model results. The Shallow Water Equation set, Eulerian-Lagrangian Method (SWE-ELM) was applied to the model.

Note that following modelling of the initial Detailed Design bridge, the bridge design was amended to reduce the bridge height by 400 mm and the design modelled provided greater freeboard than required to meet the Design Criteria. This change in bridge height is unlikely to increase modelled flood levels, as the bridge approaches will be lower than modelled and still provides the required freeboard above SLS2 and ULS flood levels. Therefore the model was not rerun with the lower bridge deck and approaches.

The soffit of the permanent Lami bridge has been placed above the SLS2 river flow dominated flood event + 1.2m freeboard and ULS river flow dominated event + 0.6m debris clearance. With the current 100% Detailed Design stage design flood levels there is 1.3m freeboard to the minimum bridge soffit of 4.1 mRL at the abutment, in the SLS2 river dominated flood event, and there is 0.9m freeboard to the bridge soffit in the ULS river dominated flood event. The existing bridge deck level is 4.3 mRL at the road tie-in, and the proposed bridge deck level is 5.3 mRL at the same location, along the road centreline. As a result, the road will be lifted by approximately 1.0 m at abutments.

Because the SLS2 flood event + 1.2 m freeboard is higher than the ULS flood event + 0.6 m clearance, the bridge superstructure is not expected to be submerged during ULS design events.

3.6.3 Navutu

For the SLS2 event, FRA have requested a minimum freeboard of 0.6 m to the bridge soffit level at this site, to reduce the need for retaining walls and make the tie-in to the adjacent rail track easier. As stated in RFI 451, the critical modelled SLS2 design flood level was 4.1 mRL using the SWE-ELM model equation set. In NTC 605, FRA agreed to lower the road level to 6.2 mRL, 0.7 m lower than previously agreed and an increase of 0.9 m on the existing road level.

At the 100% Detailed Design stage, the Navutu flood model was rerun to account for refinements in the design, and the SLS2 river-dominated design flood level decreased to 4.0 mRL. The bridge structure depth is 1.2 m. For these final flood model results, the achieved freeboard to the bridge soffit is 1.0 m in the SLS2 flood event, and 0.0 m in the ULS flood event. Because ULS flood level plus 0.6m debris clearance requirement as per AS5100.2 is not achieved, the bridge superstructure was designed to resist ULS flood water forces.

3.6.4 Vunitogoloa

a. Permanent Bridge

At the 100% Detailed Design stage, we updated and reran our flood model using the latest bridge and road approach design. In this model run we also changed the model equation set at the request of our external reviewer. These changes to the model caused the modelled flood levels to increase. The modelled SLS2 level increased from 3.9 mRL to 4.0 mRL, to be at the same elevation as the agreed deck level. The previously agreed deck level will not be raised further due to the conservatism in the modelled water levels described below.

The extent of the modelled terrain is small due to the absence of detailed DEM/survey that covers a wider area. We have conservatively applied the entire catchment flow to the upstream boundary of our model. However, our analysis of satellite imagery and the low-resolution 30-m grid elevation models suggests that a portion of this flow will not reach the bridge and will overtop Kings Road in the floodplain to the west of the site. This would result in flood levels and velocities being lower than what we have reported, as such a precautionary approach to the modelling has been adopted.

NTC482 specified a minimum finished road level of 4.0 mRL shall be adopted to keep the road serviceable during SLS2 flood event. The existing finished road level is 2.8 mRL, resulting in approximately 1.2 m road lift. FRA requested to minimise the road lift to avoid negative impacts on the Vunitogoloa Village. The finished road level of 4.0 mRL results in the soffit level of approximately 2.9 mRL (4.0 mRL - 0.9 m bridge superstructure – 0.2 m cross fall).

The SLS2 flood level is at the same level as the minimum finished road level of 4.0 m RL. FRA has been appraised on (refer RFI 346) and accepted the increased risks to the bridge structure and approach formations. FRA has also acknowledged that additional maintenance such as debris removal will be required, due to having no freeboard to the SLS2 and ULS event flood levels.

Because ULS flood level plus 0.6 m debris clearance requirement as per AS5100.2 is not achieved, the bridge superstructure was designed to resist ULS flood water forces.

b. Temporary bridge

NTC497 specified that a minimum finished road level of 4.6 m RL shall be adopted. The finished road level of 4.6 m RL results in the soffit level of approximately 3.9 m RL (4.6 m RL – 0.7 m bridge superstructure).

At the time of level setting the SLS1 flood level was 3.2 m RL, which resulted in 0.7 m freeboard between the SLS1 flood level to the temporary bridge soffit level of 3.9 m RL. With the current 100% Detailed Design flood model results, the SLS1 flood level has since gone up to 3.5 m RL, which now results in 0.4m freeboard between the SLS1 flood level and the temporary bridge soffit level of 3.9 m RL.

The previously agreed temporary bridge finished road level of 4.6 m RL will not be raised further, due to limitations in bridge height to ensure appropriate tie-ins with the existing road.

Because the soffit of the temporary bridge has not been positioned above ULS flood event of 3.9 m plus 0.6 m debris clearance, there is an increased risk that the temporary bridge modular steel superstructure may be damaged in the ULS flood event. The temporary bridge superstructure has not been designed to resist ULS flood water forces, or for the impact of the floating debris or logs that may be conveyed in the river in the ULS flood event.

3.6.5 Viseisei

The Viseisei design bridge superstructure elevation, and achieved freeboard, varies along the bridge length (refer to structural drawing 6103677-SE-B05-51). The lowest point of the deck is at the east abutment, where the deck elevation is 4.7 mRL. The highest point of the deck is at Pier A, where the deck elevation is at 5.2 mRL. The bridge structure depth is 1.0 m. Table 3-6 shows the calculated freeboard between the modelled flood levels and the bridge soffit.

For the SLS2 event, FRA have requested a minimum freeboard of 0.6 m to the bridge soffit level at this site. The achieved freeboard is greater than 0.6 m for most of the bridge length, but drops to 0.6 m at the eastern end of the bridge where the deck is lower in the SLS river-dominated event. The eastern end of the bridge is away from the main part of the channel and so will be subject to lower water velocities and subject to less debris than in the centre of the river.

It is expected that the bridge superstructure will be partially submerged during the ULS event. This has been discussed with and confirmed by FRA during meeting held on 2/12/2022 (refer also RFI 346 and RFI 347 submitted on the 22 December 2022). FRA confirmed it does not want to lift the bridge above the ULS flood event to minimise the road lift and the related land impacts.

Table 3-6: Viseisei freeboard to soffit level

Location	Deck level (mRL)	Soffit level (mRL)	SLS2 1/100 river flow dominated	SLS2 1/100 tide dominated	ULS 1/1000 river flow dominated	ULS 1/1000 tide dominated
			Achieved freeboard to bridge soffit level (m)			
East abutment	4.7	3.7	0.6	0.5	0.1	-0.5 (above soffit)
Pier A	5.2	4.2	1.1	1.0	0.6	0.0 (at soffit)

3.6.6 Vitawa

a. Permanent Bridge

NTC482 specified a minimum finished road level of 5.8m RL shall be adopted. The existing finished road level is 3.5m RL, resulting in approximately 2.3m road lift.

The finished road level of 5.8m RL results in the soffit level of approximately 4.7m RL (5.8m RL - 0.9m bridge superstructure – 0.2m cross fall). This matches the estimated SLS2 sea level dominated flood level. With reference to RFI 451 and NTC482, FRA confirmed it is not desired to further lift the road to provide the serviceability freeboard of 0.6m. FRA has been appraised on (refer RFI 346) and accepted the increased risks to the bridge structure and approach formations and an additional maintenance such as debris removal that may be trapped due to no freeboard.

Because ULS flood level plus 0.6m debris clearance requirement as per AS5100.2 is not achieved, the bridge superstructure was designed to resist ULS flood water forces.

b. Temporary Bridge

The proposed bridge at Vitawa is on the same alignment as the existing bridge, and so a temporary crossing of the river is proposed just upstream of the existing bridge. The temporary crossing will be twin 1800 mm diameter culverts, with a crossing deck level of 3.6 mRL. This is below the 4.0 mRL SLS1 design flood level for the 25-year ARI flood event, and so the crossing would be expected to flood during a significant flood event.

3.6.7 Navola

a. Permanent bridge

As the Navola road bridge crosses the stream, the bridge is rising from west to east where the road is cut into a bluff. As such, the permanent bridge level is higher than required to meet Design Criteria requirements for freeboard. The bridge soffit has been set at least 1.0m above the ULS flood level at the western abutment and rising to over 2 m at the eastern abutment as the road rises. There is at least 1.3m freeboard to the bridge soffit in the SLS2 modelled flood event. Therefore, the bridge meets design criteria requirements for freeboard and is not expected to be submerged during SLS or ULS flood events. The road will be lifted by a minimum of 2.4m at the bridge location.

This approach has been followed to reduce flood forces, debris accumulation and obstruction to flow due to water trapping against the pier piles and headstocks, which are not aligned parallel to the river flow (due to limitations on bridge skew angle for bridges without expansion joints). Lifting the bridge also reduces the extent of rock cutting required.

b. Temporary pedestrian crossings

The realignment of the road to accommodate the proposed bridge will result in temporary closure of pedestrian access to properties on the left (Suva) of the stream, upstream of the bridge. To mitigate this, two temporary pedestrian access routes have been proposed. Refer to the B07 Navola Bridge Design Report for details.

3.6.8 Matawalu

The Matawalu site lies on the edge of a wide floodplain that extends beyond the extent of the survey used for the bridge modelling. Therefore, a sensitivity model run was undertaken, to account for the extent of survey being insufficient to define flow paths around the bridge and showing water spilling out of the river upstream of the modelled area. The sensitivity modelling was done using a 30 m grid global DEM (Copernicus GLO-30) that encompasses the valley/floodplain and bridge site. The sensitivity model was run for the SLS2+10% and ULS+10% flood events to see where water spills out upstream of the river channel, and to estimate the amount of water bypassing the surveyed bridge model area. The upstream boundary of the sensitivity model was placed across a narrow point in the floodplain, upstream of where the whole catchment flow is expected to be contained. The downstream boundary of the sensitivity model was set at the coast. The lateral extent of the sensitivity model was set at the edges of the floodplain.

The sensitivity run indicated that water spills out of the river channel upstream and bypasses the bridge, resulting in only 58% and 49% of the peak SLS2 and ULS flow, respectively, being conveyed through the bridge (Figure 3-1). Based on these results, the detailed bridge model was rerun, but with a factor of 0.58 applied to the SLS flow hydrograph and 0.49 applied to the ULS flow hydrograph, and the resulting flood levels at the bridge were extracted. Note that if 100% of the catchment design flow was routed through the bridge section, then flood levels would be approximately one metre higher. The 58% flow factor was also applied to modelling of the temporary bridge.

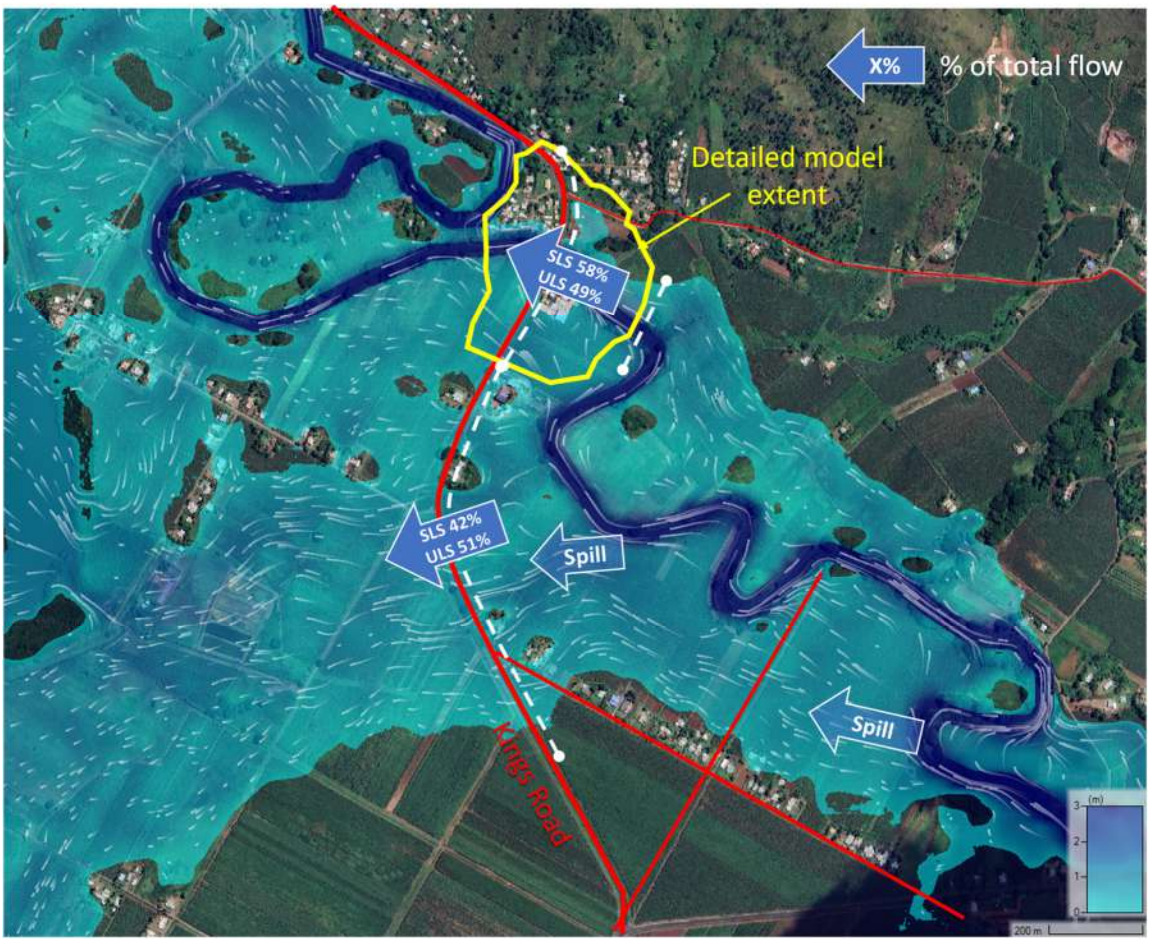

Figure 3-1 Bypass Flow Estimation for Matawalu

The peak water levels for the SLS2 and ULS events occur with normal depth (ND) downstream flow conditions rather than with the downstream water level set based on extreme event sea levels.

a. Permanent Bridge

During Detailed Design, prior to the sensitivity analysis, the bridge superstructure was designed to resist ULS flood water forces, because ULS flood level plus 0.6 m debris clearance requirement as per AS5100.2 was not achieved if the full catchment design flow is modelled. This approach follows discussion and agreement with FRA during meeting held on 2/12/2022 (refer also RFI 346 and RFI 347 submitted on the 22 December 2022) where FRA confirmed it does not want to lift the bridge above the ULS flood event to minimise the road lift and the related land impacts. FRA requested to reduce 1.2 m freeboard proposed by BICL to 0.6 m to minimise road lift and the related short-term safeguards impacts (refer also NTC 372 and meeting held on 1 February 2023).

Following the sensitivity modelling to estimate the flow bypassing the bridge, and the subsequent remodelling with the revised (lower) flows, the bridge level has been set above the debris clearance requirement, as agreed in RFI 630. The bridge deck has been set at 6.7 mRL and the soffit of the permanent bridge has been set at 5.5 mRL. This is 1.2 m above the SLS2 flood level (4.3 mRL) when the estimated bypass flows are accounted for, and more than 600 mm above the ULS flood level.

b. Temporary Bridge

The soffit of the temporary bridge has been placed at 4.9 mRL, above the greater of the SLS2 flood event plus 1.2m freeboard or the ULS flood event plus 0.6m debris clearance. As a result, the temporary bridge is not designed for flood water forces.

3.6.9 Sabeto

As with other bridges, the flood model was based on survey covering a small area of the river and floodplain due to the absence of DEM/survey covering a wider area. At the Concept Design stage, the Diffusion Wave (DW) equation set was used for the modelling with the whole catchment design flow routed through the limited model extent. This was the model presented for external review in February 2023.

In July 2023, the External Reviewer commented that the SWE should be used to provide better definition of water levels around the bridge and that this would include better representation of the effects of momentum, especially super-elevation of water levels around the outside of the bend upstream of the bridge.

Use of the SWE Eulerian-Lagrangian Method (SWE-ELM), with no change to the model extent or design flow, results in a material increase in average flood levels immediately upstream of the bridge of about 200-300 mm, but with bigger increases at the southern abutment on the outside of the bend; there being 400-500 mm difference in modelled water levels between the inside and outside bends of the river at the bridge.

Use of SWE-ELM compounds a conservative approach to the flood modelling, that assumes all the design flow for the catchment is conveyed through/via the bridge and area of the limited survey extent. In a large floodplain, such as Sabeto, this ignores the potential for floodwaters to be conveyed on the wider (unsurveyed) floodplain and assumes 'glass-walling' at the edge of the modelled extents. All other things being equal, this approach will generate modelled flood levels that are higher than would occur.

To moderate the conservativism of a model using limited survey extent with significant glass walling and the SWE set, the model extent was revisited. Without detailed survey/DEM of the whole floodplain/valley, this is not possible to do in any detail. However, we estimated the flow passing through our surveyed bridge model extent by using a simple 2D model of the wider area based on a satellite-captured digital elevation model (Copernicus GLO-30) with a 30 m horizontal resolution DEM grid. This does not provide the detail required for accurate modelling, but it can be used to identify significant overland flow paths that divert water away from the detailed model area.

In the case of Sabeto, using the 30 m DEM indicates (Figure 3-2) that water will spill out of the river about 600m upstream of the bridge, with 30%-40% of the total river bypassing to the south of the bridge (outside of the modelled area), while about 10% of the flow bypasses to the north.

Though approximate, this suggests that only 50%-60% of the flow passes through the small extent of the detailed model, which would reduce modelled flood levels at the bridge.

A check of the SWE model results indicated that the SLS and ULS design flood levels (based on the DW model runs at Concept Design) are achieved with about 80% of the total design flow. This is more than the 50% estimated from the 30 m grid model and so the DW-based design levels are likely to be conservative.

Given the uncertainty over how much flow bypasses the modelled area, it is prudent to retain flood levels used to set the bridge level despite these being based on conveying the full flow through the detailed model area and using the Diffusion Wave equation set, as these are higher than the modelled flood levels using the SWE-ELM equation set and reduced flow through the detailed model area.

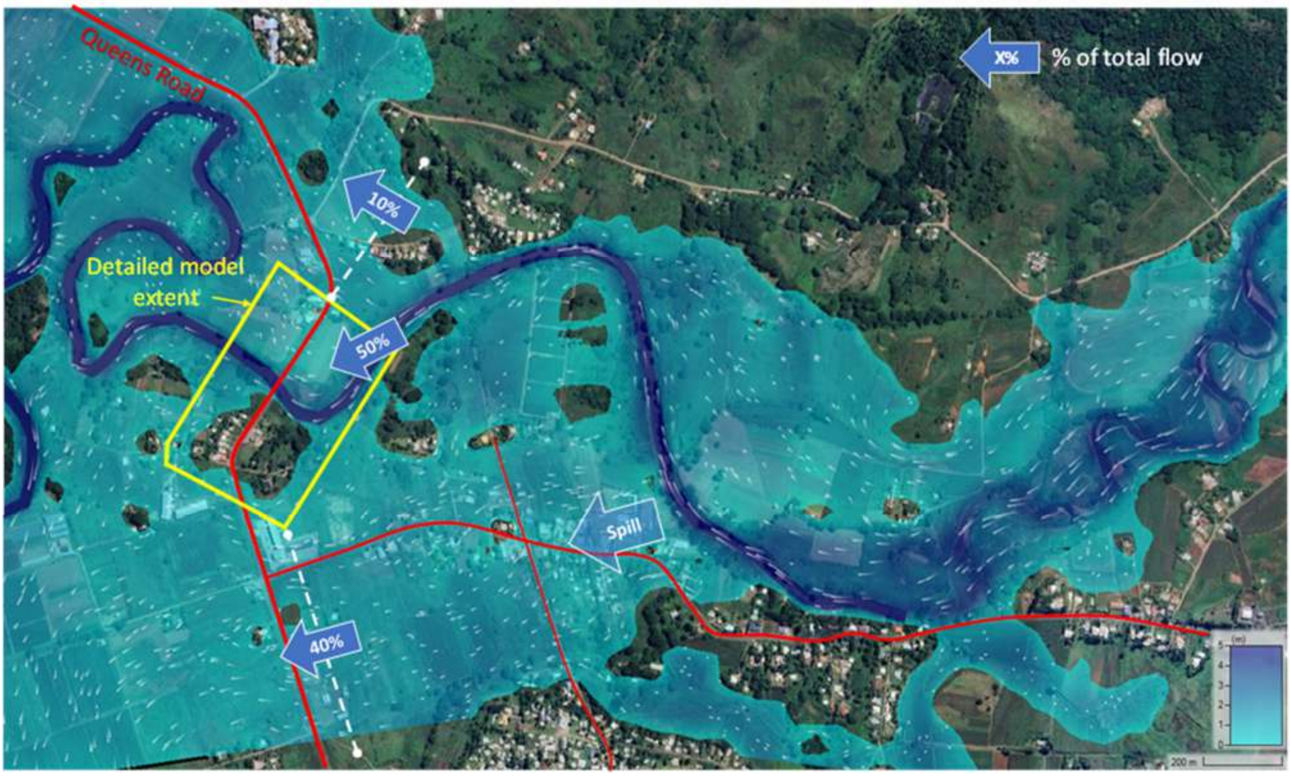

Figure 3-2 Bypass Flow Estimation for Sabeto.

3.6.10 Lomolomo

The Lomolomo flood model geometry is based on local photogrammetry and topographical surveys. Due to the limited survey extent across the Lomolomo Bridge floodplain, the modelled terrain has been extended using a satellite-captured digital elevation model (DEM) with a 30 m grid (Copernicus GLO-30). Use of the 30 m DEM improves the representation of how much flow reaches the bridge, and therefore improves the confidence in the flood model results. The Shallow Water Equation set, Eulerian-Lagrangian Method (SWE-ELM) was applied to the model.

A revised road level of 3.5m RL shall be adopted for the Lomolomo permanent bridge alignment, as per RFI 649 and NTC 672. The finished road level was reduced from the previous design height of 4.6m RL to minimise the rock cutting work required and to improve integration with existing infrastructure. The existing finished road level is 2.3m RL, resulting in 1.2m lift to the revised proposed road level. The finished road level of 3.5m RL results in the bridge soffit level of approximately 2.3m RL (3.5m RL – 1.2m bridge superstructure).

The SLS2 river flow dominated flood level of 3.2 mRL is above the bridge soffit level at 2.3 mRL, and no freeboard is provided. However, floodwaters are unlikely to inundate the road itself in a SLS2 flood event. During a ULS storm surge event, the bridge will likely be fully submerged and impassable due to floodwaters. This represents a departure from the agreed design criteria, as acknowledged in RFI 649 and NTC 672.

FRA has been appraised on (refer RFI 649) and accepted (NTC 672) the increased risks to the Lomolomo bridge structure and approach formations. FRA has also acknowledged that additional maintenance such as debris removal will be required, due to having no freeboard to the SLS2 and ULS event flood levels. Refer to RFI 346 for further details.

Because ULS flood level plus 0.6m debris clearance requirement as per AS5100.2 is not achieved, the bridge superstructure was designed to resist ULS flood water forces.

4 Review and Verification

It is acknowledged that the hydrological and flood modelling for the Fiji 40 Bridges project has been based on limited hydrometric and survey information. Yet the modelling needs to be sufficiently robust to allow the flood risk to be accommodated in the design, and for Fiji Roads Authority to understand the resilience and residual risks from flooding, especially where the bridge level has been lowered below design criteria for flooding to accommodate other demands, such as tie-in to local access or land availability.

As each process of the hydrological and hydraulic modelling has been undertaken, the Waterways Team have discussed the modelling approach with senior modellers within BICL.

For each bridge, the review and verification process has included:

- Check of hydrological inputs (export from HEC-HMS model).
- HEC-RAS model review. Reviewer comments recorded in a review form and saved as a signed PDF.
- Review of Modelling Summary Sheet
- Review of Concept/Detailed Design Bridge Report, and cross-check of results against those reported in the Summary Sheet and on drawings.
- Review and completion of the Departures Sheet, noting departures from design criteria.
- Sign-off of the Hydrology section on the multi-discipline Verification Form.
- We have also provided responses to review comments from FRA and Beca's external reviewer, SMEC. This has including providing SMEC with zipped copies of the HEC-RAS model files for the relevant modelled scenarios.

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A

Appendix A – Individual Bridge Summary Sheets

Bridge		Summary sheet	Design stage
1.1	Medraukutu	Provided	100% Detailed Design
1.2	Lami	Provided	100% Detailed Design
1.3	Navutu	Provided	100% Detailed Design
1.4	Vunitogoloa	Provided	100% Detailed Design
1.5	Viseisei	Provided	100% Detailed Design
1.6	Vitawa	Provided	100% Detailed Design
1.7	Navola	Provided	100% Detailed Design
1.8	Matawalu	Provided	100% Detailed Design
1.9	Sabeto	Provided	100% Detailed Design
1.10	Lomolomo	Provided	100% Detailed Design

1.1 Medraukutu Bridge

Bridge Priority:	Priority 1	**Name:**	Medraukutu Bridge
Road:	Queens Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	3.6 mRL	**Design bridge deck level:**	4.8 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Monica Hoetjes	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Last model review date:**	8 September 2023

Comments:

Situated on the Queens Road west of Suva, the existing bridge is arched and higher than the road approaches. The bridge is on the coast and so flood levels will be dominated by extreme sea levels, though exacerbated by runoff from the upstream catchment. Upstream of the bridge, there are dense mangroves in across the creek, and mangroves coat the banks of the bay downstream of the bridge. There are houses on ground lower than the road on the upstream west bank.

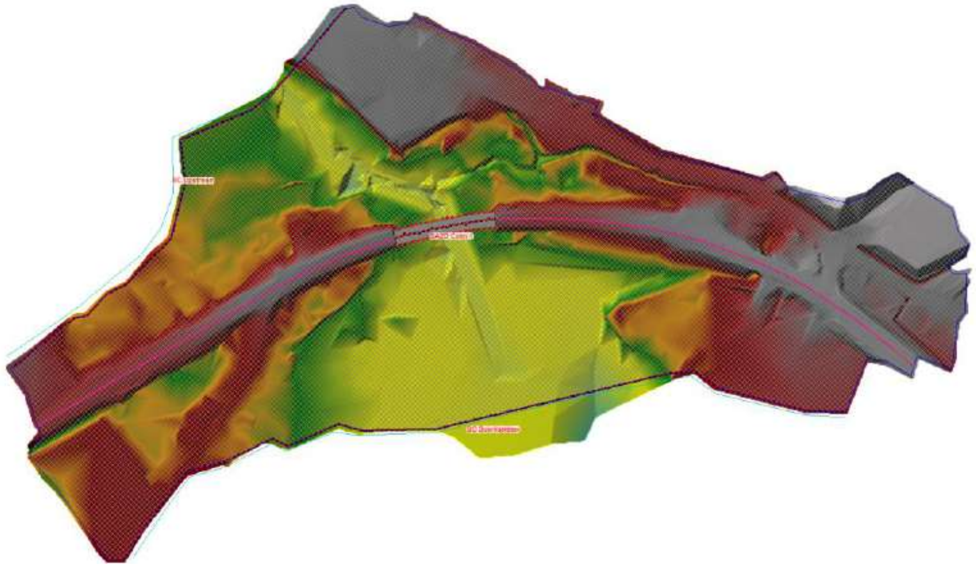
Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. However, this is an accepted limitation of the modelling and the terrains created are the best with the information available.

This model and results are not to be used for other purposes.

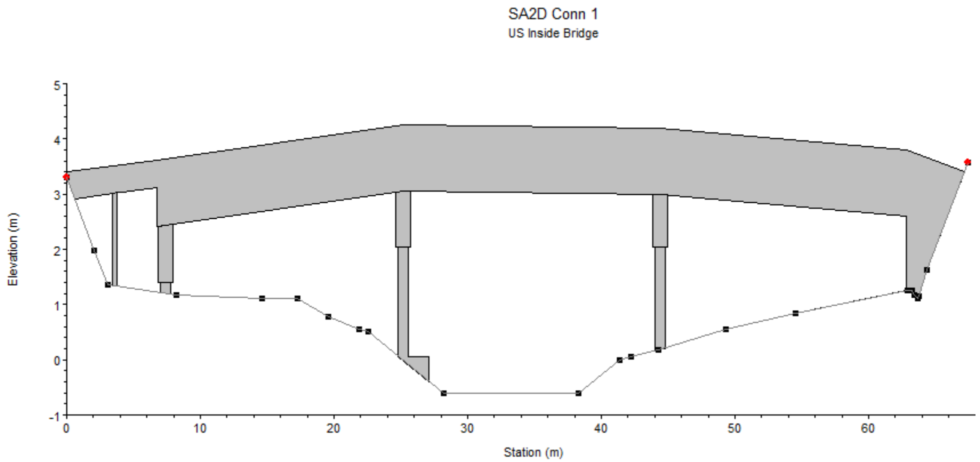
1.1.1 Existing Bridge

Medraukutu bridge aerial

From downstream elevation (FRA, 2016)

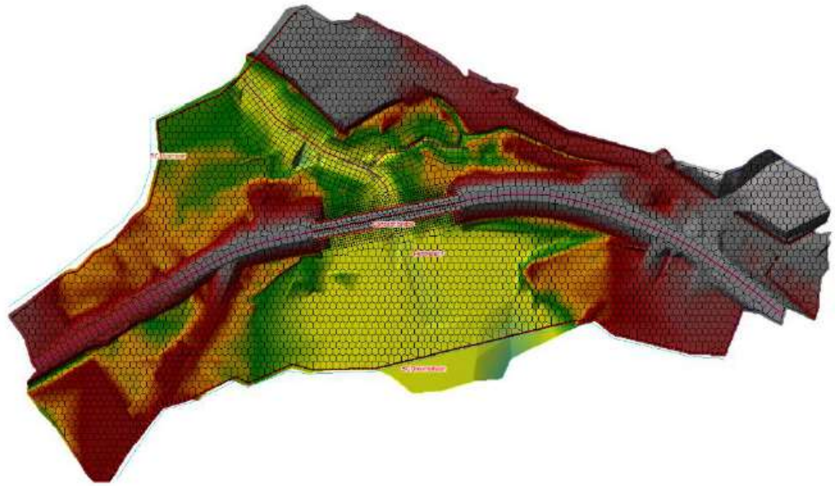


Existing bridge HEC-RAS model layout

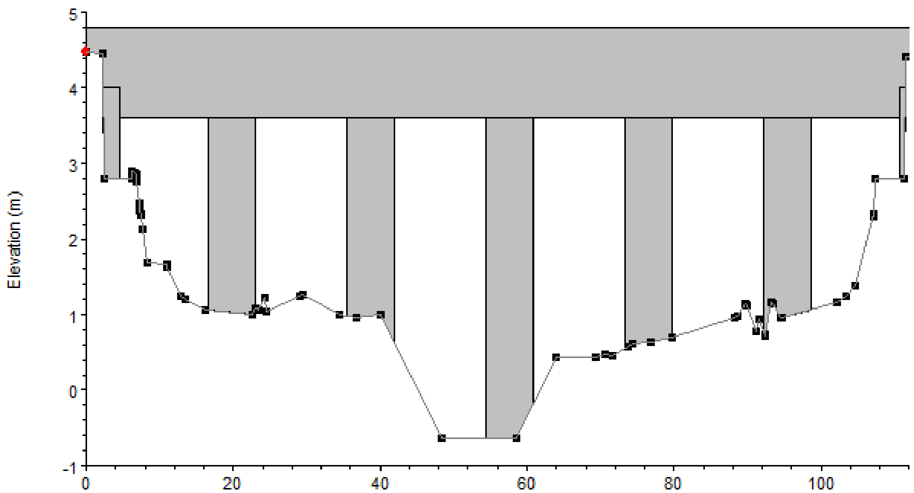


Existing bridge geometry

1.1.2 Design Bridge



Design bridge HEC-RAS model layout



Design bridge geometry

1.1.3 Temporary Bridge

No temporary bridge has been modelled for this location.

1.1.4 Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	2.5				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	2.6				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	Not reported, WSE < Run 4				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	3.0				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	2.3	1.8	3.0		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		2.5	3.3		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	2.8			1.6	2.0
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	3.0				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	Not reported WSE < Run 10			1.6	2.1
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	3.3				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	2.6				2.4
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	2.8				2.6

Lami Bridge

Bridge Priority:	Priority 1	**Name:**	Lami Bridge
Road:	Queens Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	Modelled soffit levels: 4.5 to 4.9 mRL Final design soffit levels: 4.1 to 4.5 mRL	**Design bridge deck level:**	Modelled deck levels: 5.7 to 6.1 mRL Final design deck levels: 5.3 to 5.7 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Hans Ching / Monica Hoetjes	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Latest model review date:**	20 February 2024

Comments:

Due to the limited survey extent across the Lami Bridge floodplain, the modelled terrain has been extended using a satellite-captured digital elevation model (DEM) with a 30 m grid (Copernicus GLO-30). Use of the 30 m DEM improves the representation of how much flow reaches the bridge, and therefore improves the confidence in the flood model results.

The proposed bridge is slightly arched, with higher deck and soffit levels in the middle of the bridge than at the abutments. The bridge deck is sloped at a 3% grade down towards the upstream edge. The lower upstream bridge soffit edge has been used in the flood model.

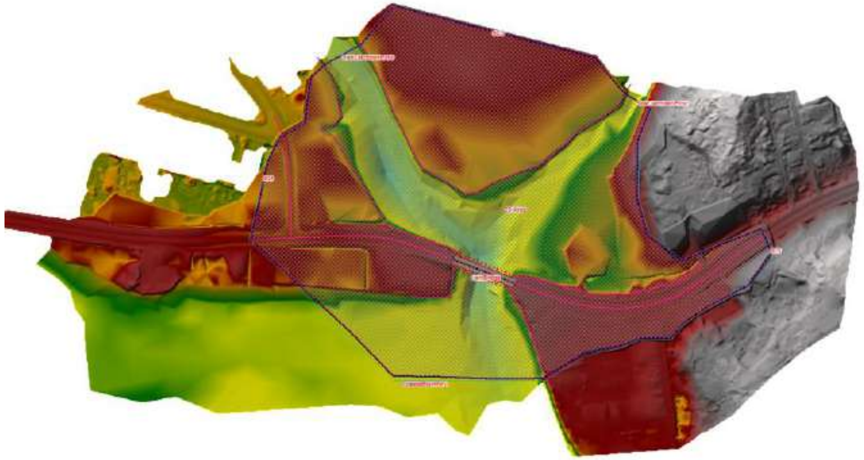
Subsequent to the final runs of the flood model, the bridge design was amended to reduce the bridge height by 400mm. This change would not make a material difference to modelled flood levels and still provides the required freeboard above SLS2 and ULS flood levels.

Note, compound bridge piers with debris rafts have been modelled as uniform piers with an effective width (for the design bridge only), due to a limitation in the modelling software. The Shallow Water Equation set, Eulerian-Lagrangian Method (SWE-ELM) was applied to the model.

This model and results are not to be used for other purposes.

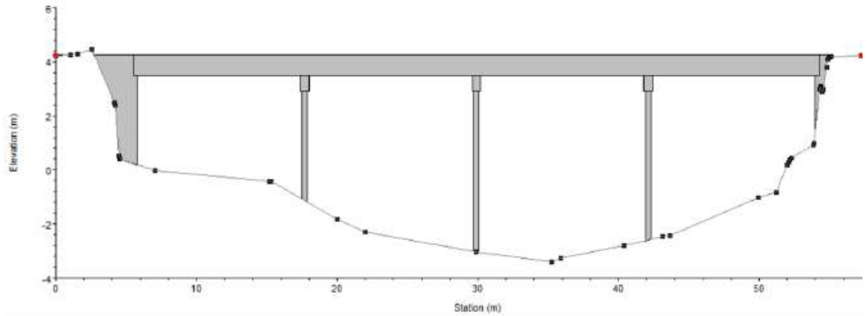
Existing Bridge

Lami bridge aerial



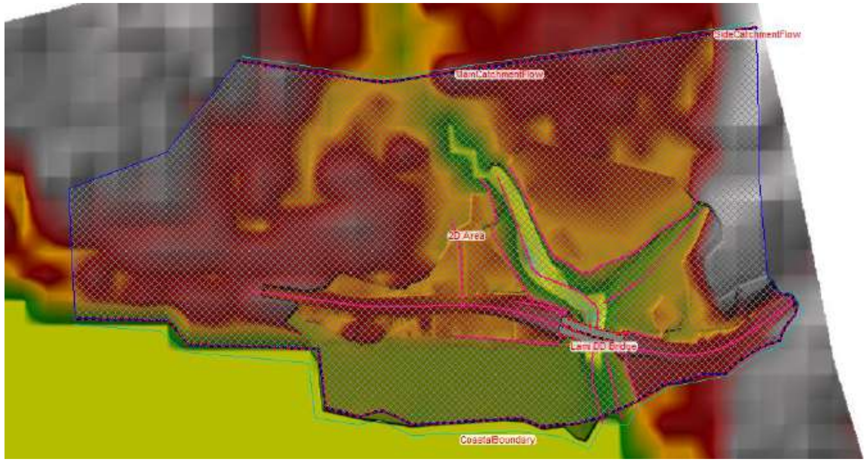
Existing bridge HEC-RAS model layout

From downstream elevation (Beca Site Visit Report, 2021)

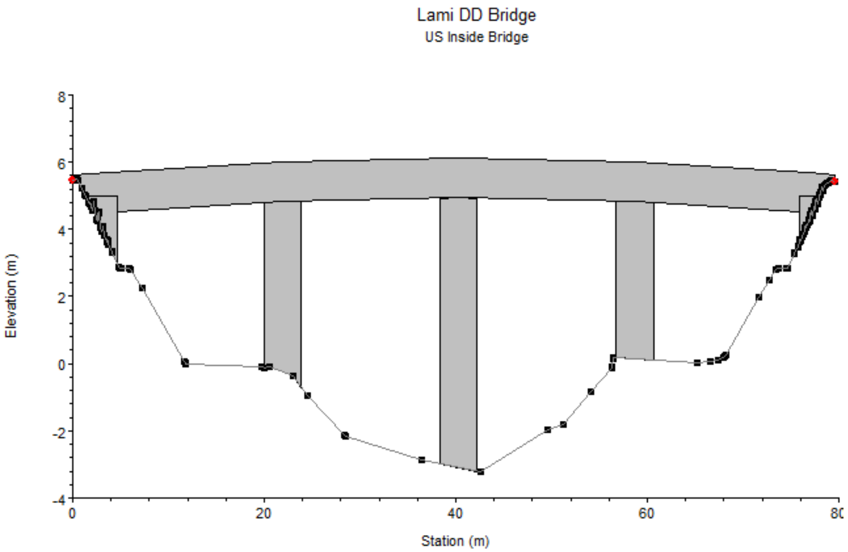


Existing bridge geometry

Design Bridge



Design bridge HEC-RAS model layout, showing extended terrain with 30 m DEM



Modelled design bridge geometry, with effective pier width. Modelled with minimum soffit of 4.5 mRL at the abutments.

Temporary Bridge

No temporary bridge has been modelled for this location

Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Approach velocity on piers (m/s)	Approach velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	2.8				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	2.8				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	3.2				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	Not reported, WSE < Run 3				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	2.7	4.8	5.8		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		5.1	6.2		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	3.2			4.3	4.3
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	3.1				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	3.6			4.5	4.5
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	Not reported, WSE < Run 9				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	3.1				4.6
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	3.5				4.8

Navutu Bridge

Bridge Priority:	Priority 1	Name:	Navutu Bridge
Road:	Navutu Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	5.0 mRL	**Design bridge deck level:**	6.2 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Monica Hoetjes	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Latest model review date:**	1 September 2023

Comments:

The Navutu bridge is located approximately 350 m from the coast of Viti Levu, in Lautoka. There is a rail bridge on the downstream side of the existing bridge. The banks of the river channel are heavily vegetated, and the bridge structures trap debris. Peak flood levels at this site are influenced by tidal levels.

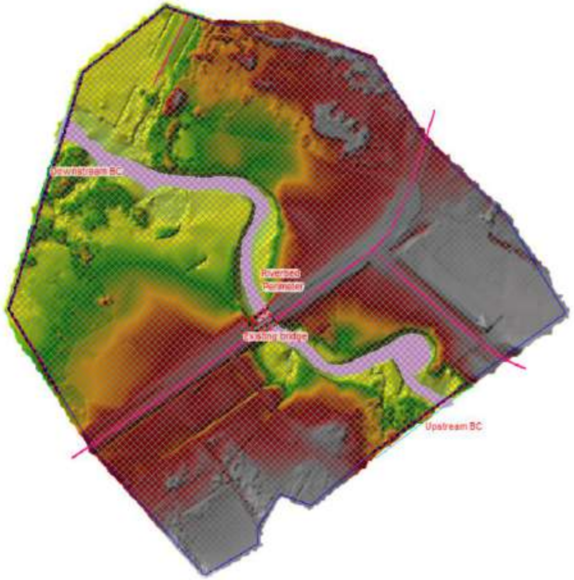
Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. However, this is an accepted limitation of the modelling and the terrains created are the best with the information available.

This model and results are not to be used for other purposes.

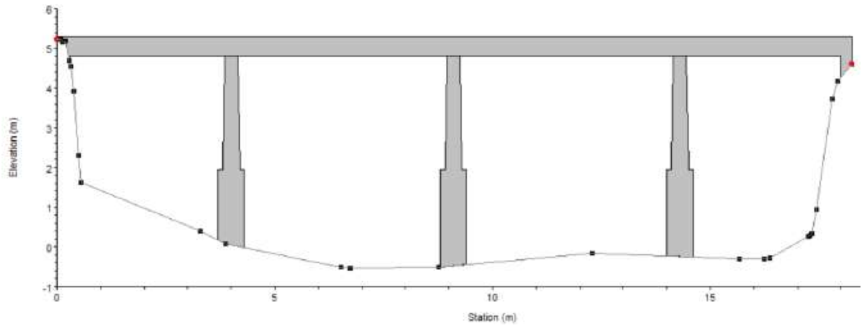
Existing Bridge

Navutu bridge aerial

From upstream elevation (FRA, 2016)

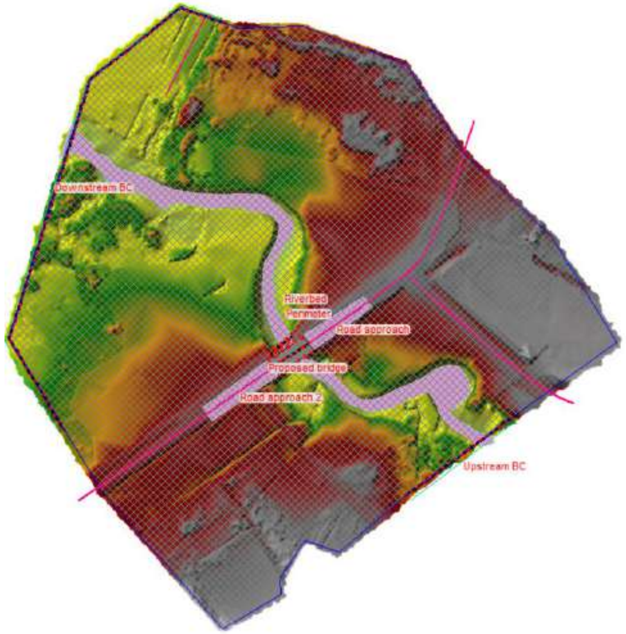


Existing bridge HEC-RAS model layout

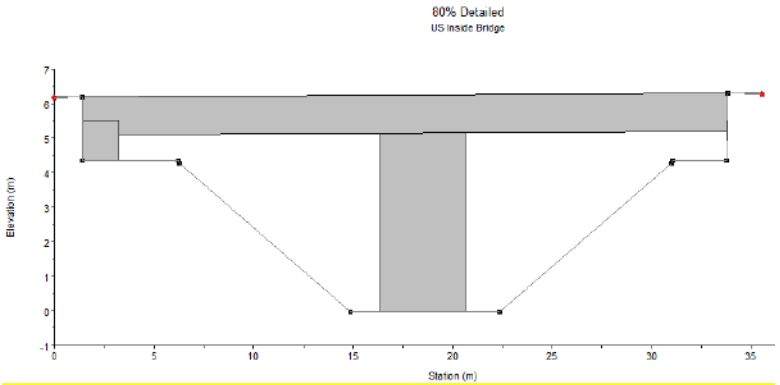


Existing bridge geometry

Design Bridge



Design bridge HEC-RAS model layout



Design bridge geometry

Temporary Bridge

No temporary bridge has been modelled for this location.

Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	4.0				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	4.1				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	Not reported, WSE < Run 4				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	4.6				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	3.9	2.8	4.0		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		3.0	4.5		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	4.8			1.5	1.6
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	5.0				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	Not reported, WSE < Run 10			1.5	1.7
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	5.4				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	4.6				1.8
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	5.0				1.8

1.4 Vunitogoloa Bridge

Bridge Priority:	Priority 1	**Name:**	Vunitogoloa Bridge
Road:	Kings Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	2.9 mRL	**Design bridge deck level:**	4.0 mRL
Temporary bridge soffit level:	3.9 mRL	**Temporary bridge deck level:**	4.6 mRL
Modeller:	Monica Hoetjes	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Latest model review date:**	19 October 2023

Comments:

The current bridge is very low-lying, with the current bridge deck less than 2m above the bed of the river, is subject to flooding and will trap debris. The site is less than 1 km from the north coast of Viti Levu and is on the boundary of where peak flood levels are affected by high sea levels or river flows. The village lies on the true right (east) bank of the river, and so tie-ins to local roads, houses, and village amenities limit the amount that the bridge can be raised. FRA requested that the permanent bridge not be raised more than 1.2 m.

Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. However, this is an accepted limitation of the modelling and the terrains created are the best with the information available. Water may spill west out of the river upstream of the modelled area, bypassing the bridge.

Note, the bridge pier with debris raft has been modelled as a uniform pier with an effective width (for the design bridge only), due to a limitation in the modelling software.

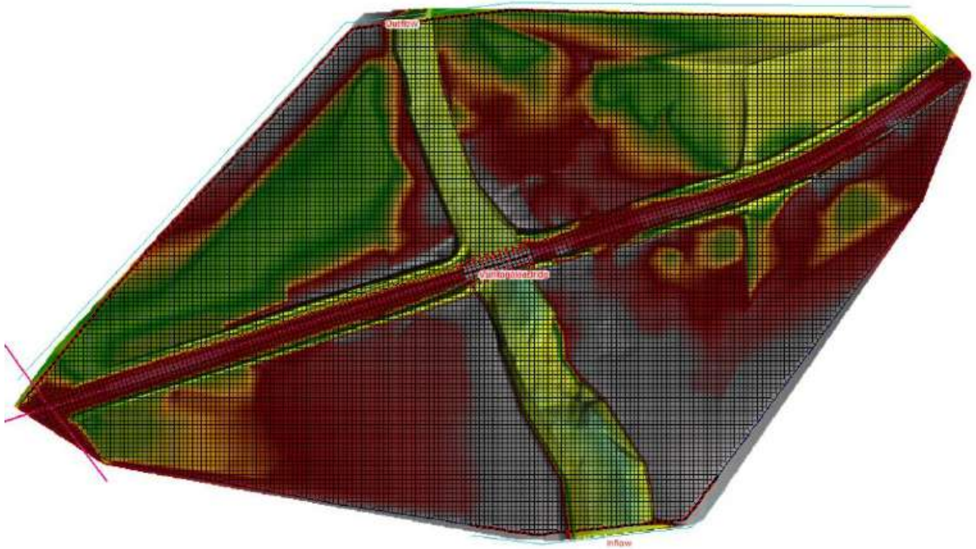
The Shallow Water Equation set, Eulerian Method (SWE-EM) was applied to the model.

This model and results are not to be used for other purposes.

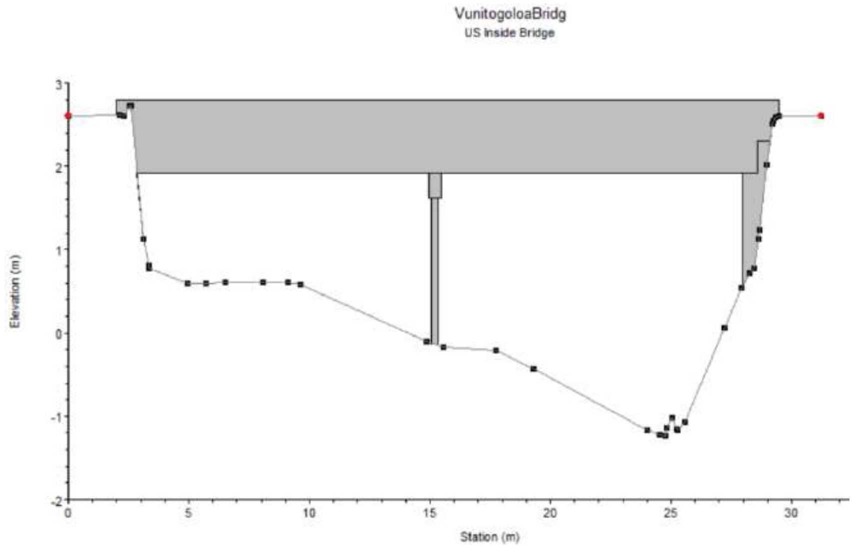
1.4.1 Existing Bridge

Vunitogoloa bridge aerial

From downstream elevation (FRA, 2016)

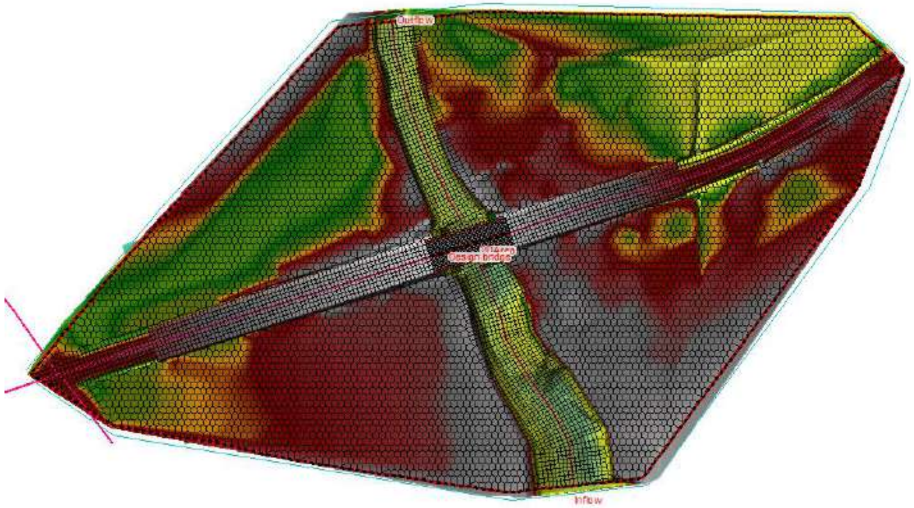


Existing bridge HEC-RAS model layout

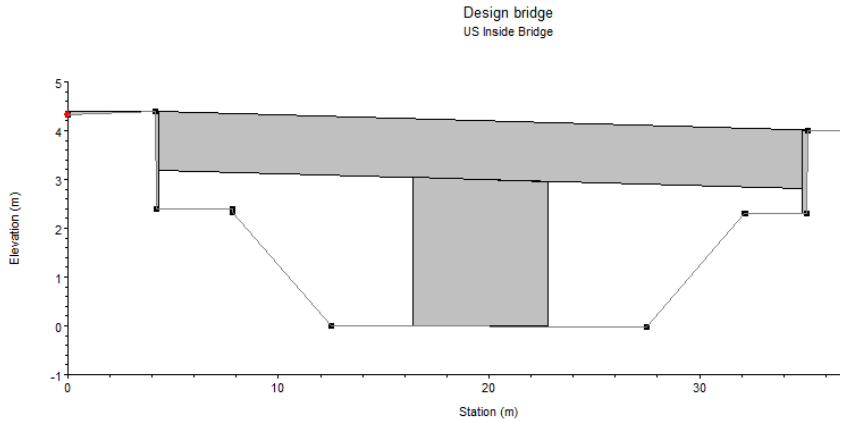


Existing bridge geometry

1.4.2 Design Bridge

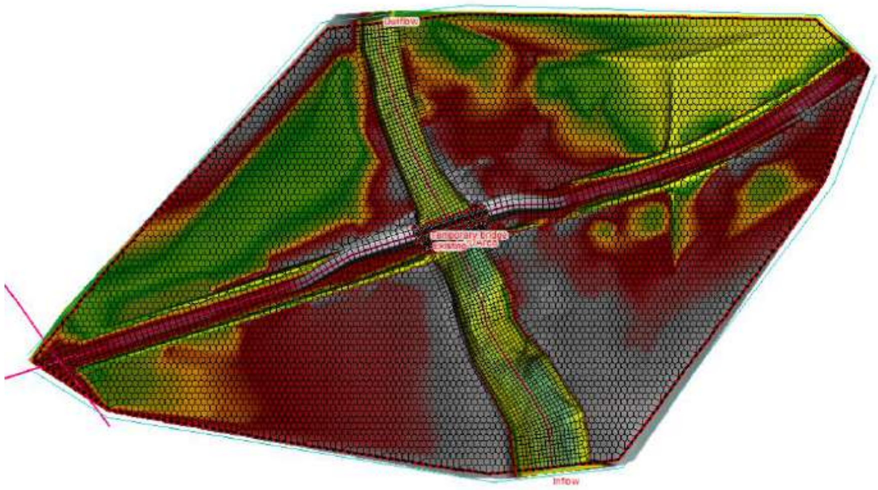


Design bridge HEC-RAS model layout

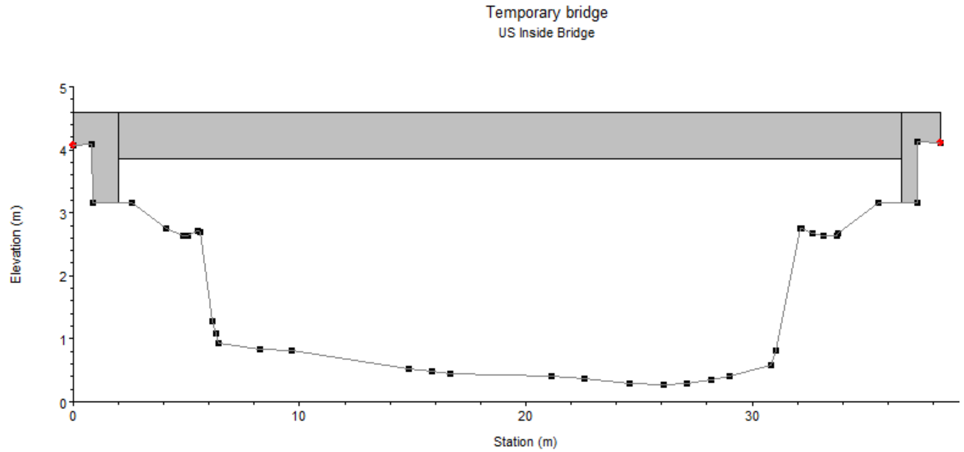


Design bridge geometry (with effective pier width based on debris and pier shape)

1.4.3 Temporary Bridge



Temporary bridge HEC-RAS model layout



Temporary bridge geometry

1.4.4 Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	4.0				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	4.0				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	Not reported, WSE < Run 4				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	4.3				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	4.1	1.7	4.1		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		1.8	4.3		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	4.3			1.6	1.7
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	4.8				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	Not reported, WSE < Run 10			1.5	1.5
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	5.2				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	4.3				1.5
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	4.4				1.5
13. Setting soffit level	Temporary	SLS1	25y no CC	10y no SLR	3.5				
14. Setting soffit level	Temporary	SLS1	10y no CC	20y no SLR	Not reported, WSE < Run 13				
15. Erosion protection	Temporary	SLS1	25y no CC	Normal depth	3.5	1.6	3.2		
16. Hydraulic loading / setting soffit level	Temporary	ULS	500y no CC	100y no SLR	Not reported, WSE < Run 17			No piers	1.8
17. Setting soffit level	Temporary	ULS	100y no CC	500y no SLR	3.9				

Viseisei Bridge

Bridge Priority:	Priority 1	**Name:**	Viseisei Bridge
Road:	Queens Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	3.7 mRL	**Design bridge deck level:**	4.7 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Monica Hoetjes	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Latest review date:**	10 October 2023

Comments:

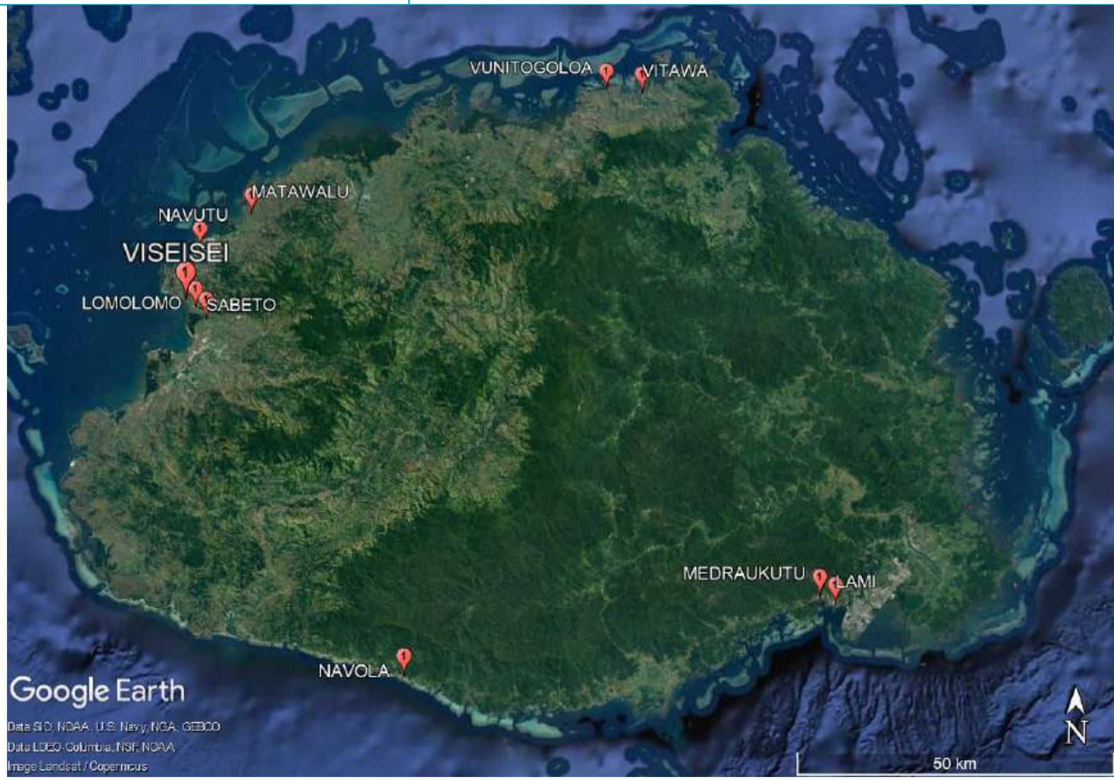
Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. However, this is an accepted limitation of the modelling and the terrains created are the best with the information available.

Notes:

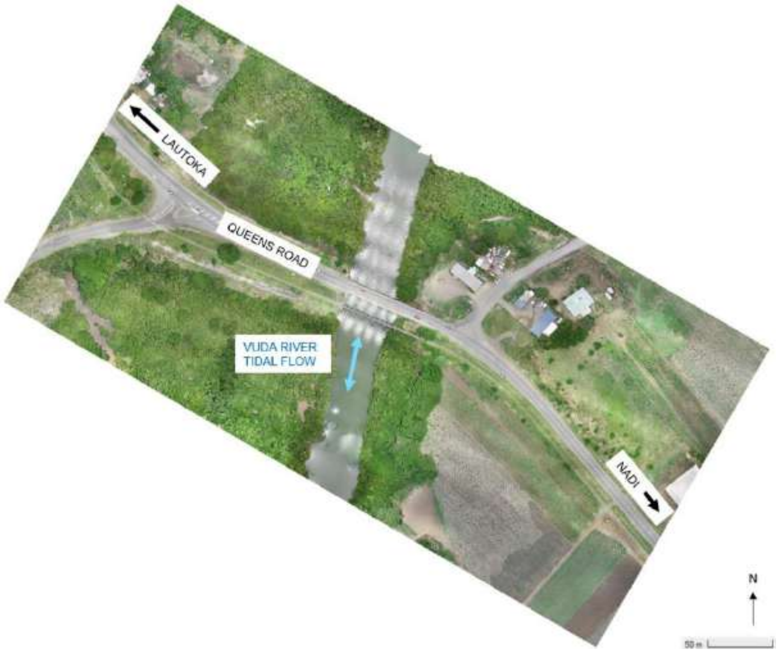
- The proposed bridge deck is modelled as 1.2 m deep resulting in a minimum soffit level of 3.5 mRL. Subsequently, the design has been changed to accommodate a 1.0 m deep deck, raising the minimum soffit to 3.7 mRL. The bridge has not been remodelled.
- Compound bridge piers with debris rafts have been modelled as uniform piers with an effective width (for the design bridge only), due to a limitation in the modelling software.

The Shallow Water Equation set, Eulerian Method (SWE-EM) was applied to the model.

This model and results are not to be used for other purposes.

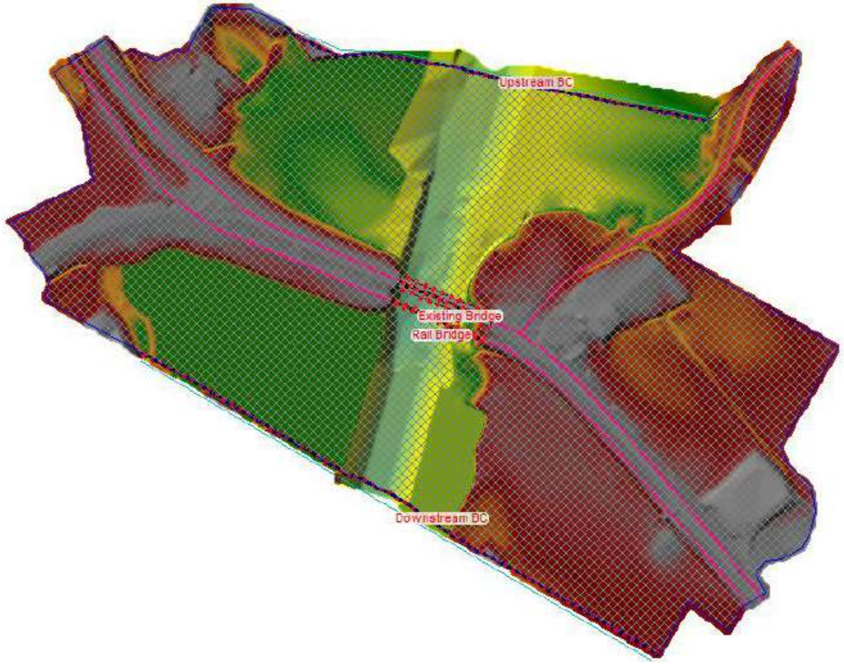


Existing Bridge

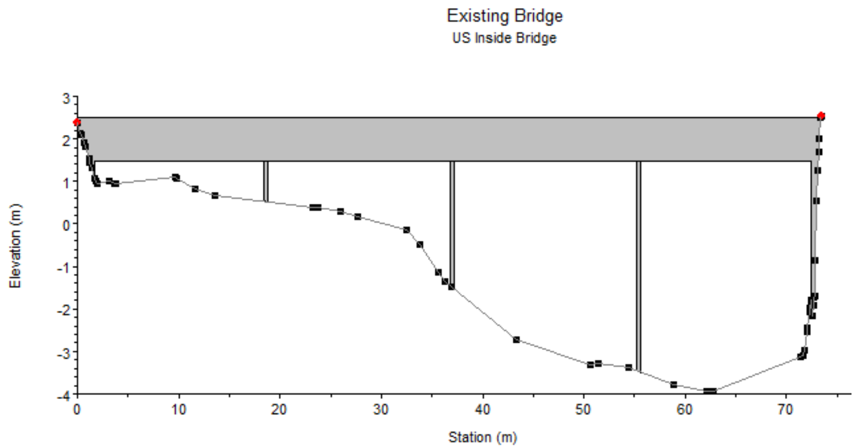


Viseisei bridge aerial

From downstream elevation (FRA, 2016)

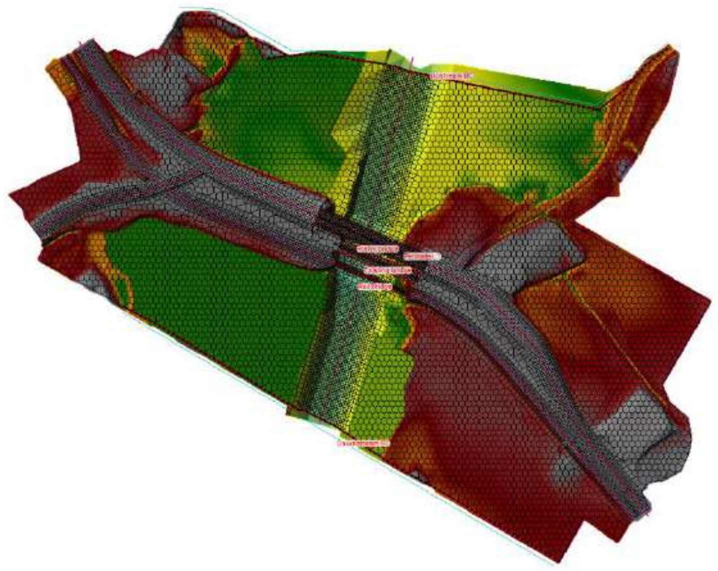


Existing bridge HEC-RAS model layout

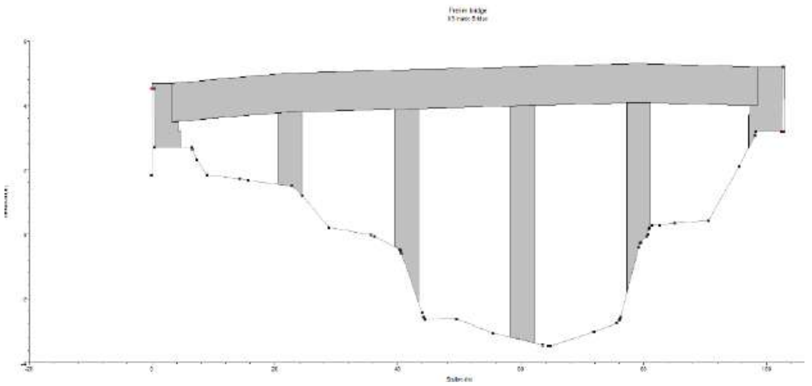


Existing bridge geometry

Design Bridge



Design bridge HEC-RAS model layout



Design bridge geometry

Temporary Bridge

No temporary bridge has been modelled for this location.

Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Approach velocity on piers (m/s)	Approach velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	3.1				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	3.2				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	Not reported WSE < Run 4				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	3.6				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	2.4	1.8	5.8		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		1.9	6.4		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	3.6			2.5	2.8
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	4.2				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	Not reported WSE < Run 10			2.7	3.0
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	4.6				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	3.2				3.5
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	3.7				3.6

1.6 Vitawa Bridge

Bridge Priority:	Priority 1	**Name:**	Vitawa Bridge
Road:	Kings Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	4.70 mRL	**Design bridge deck level:**	5.80 mRL on lower right (east) bank
Temporary culvert invert level:	0.74 mRL (Downstream)	**Temporary culvert road level:**	3.58 mRL
Modeller:	Hans Ching	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Latest model review date:**	4 September 2023

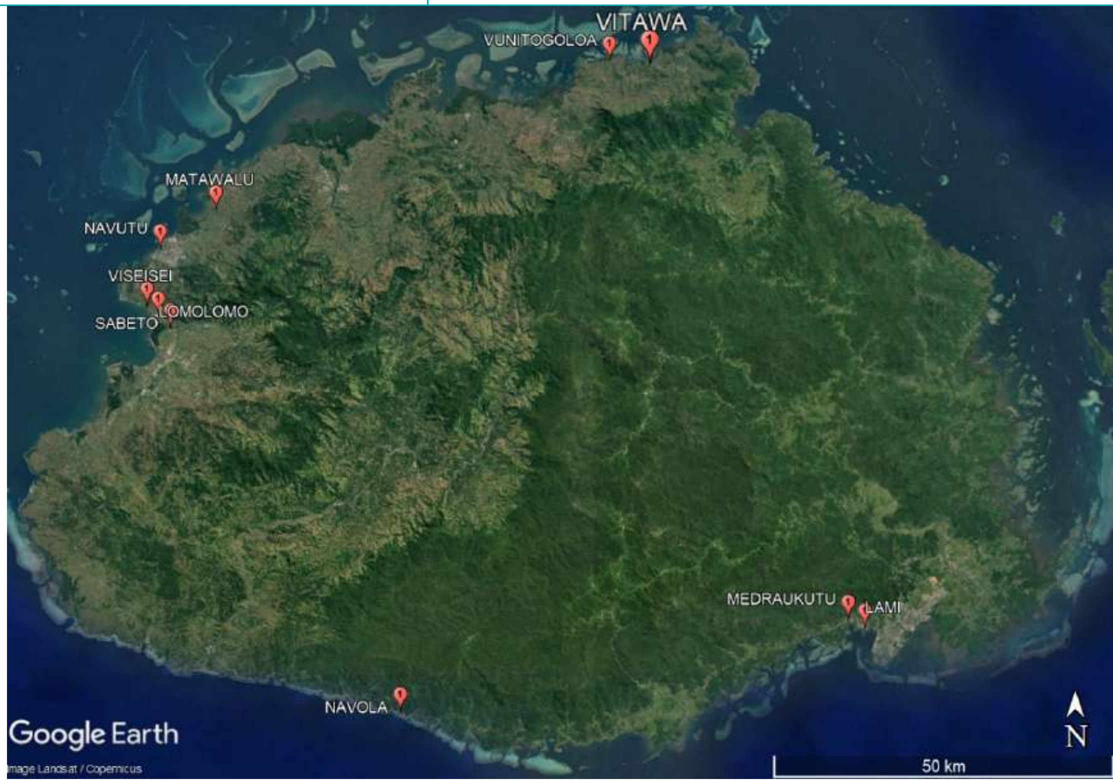
Comments:

This is about 500 m from the coast where the road crosses the floodplain of the river. The road is at grade, and floodwater will cross the road and existing bridge deck. The existing bridge soffit is less than 2 m above normal water level. Large debris can be conveyed by the river, and gets stuck under the bridge.

Twin culverts will convey low-normal flows under the temporary diversion, but this will be overtopped in flood conditions.

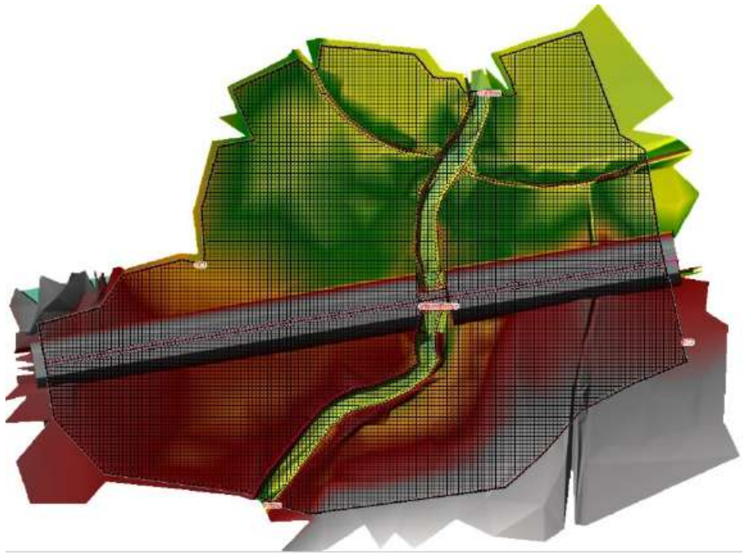
Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. However, this is an accepted limitation of the modelling and the terrains created are the best with the information available.

This model and results are not to be used for other purposes.



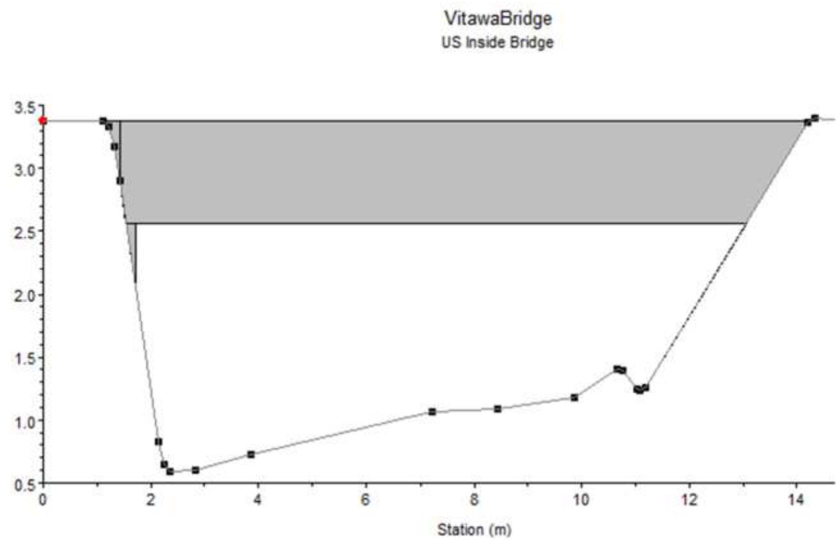
1.6.1 Existing Bridge

Vitawa bridge aerial



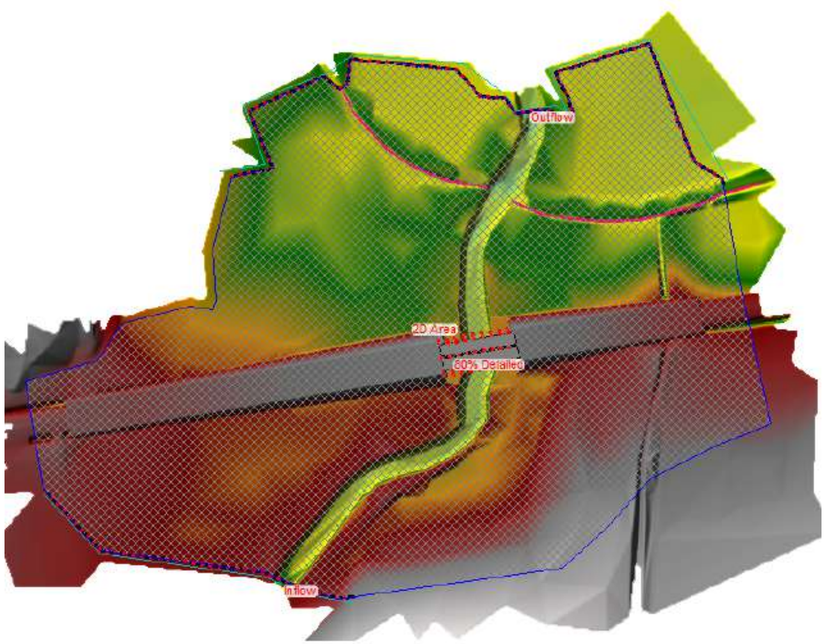
Existing bridge HEC-RAS model layout

From downstream elevation (FRA, 2016)

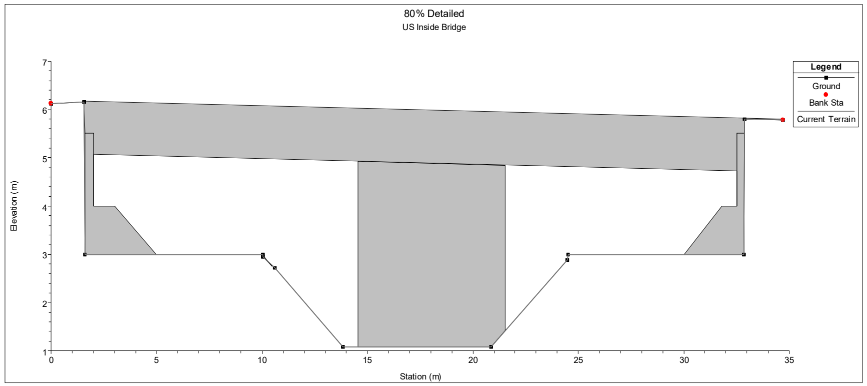


Existing bridge geometry

1.6.2 Design Bridge

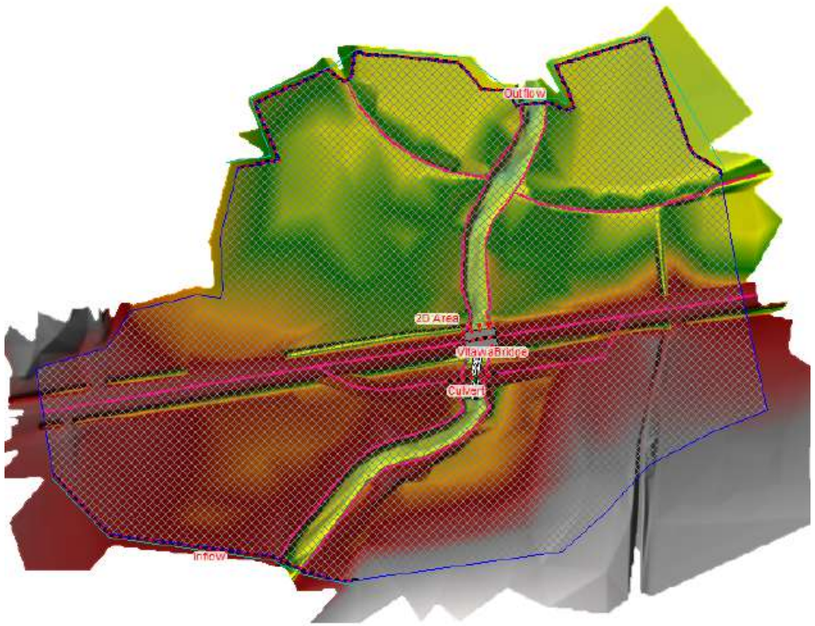


Design bridge HEC-RAS model layout

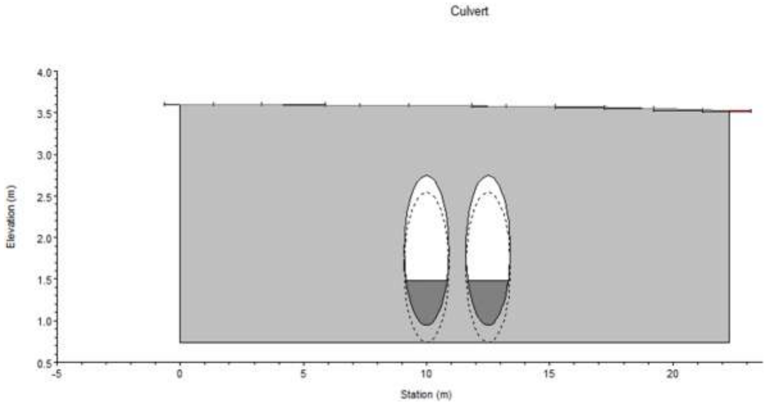


Design bridge geometry

1.6.3 Temporary Bridge



Temporary bridge HEC-RAS model layout



Temporary bridge geometry

1.6.4 Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	4.5				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	4.7				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	Not reported. WSE < Run 4				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	5.0				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	4.5	3.4	4.0		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		3.7	4.2		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	4.9			0.7	1.4
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	5.8				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	Not reported, WSE < Run 10			0.7	1.2
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	6.5				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	4.7				1.7
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	4.9				1.9
13. Setting soffit level	Temporary	SLS1	25y no CC	10y no SLR	4.0				
14. Setting soffit level	Temporary	SLS1	10y no CC	20y no SLR	Not reported, WSE < Run 13				
15. Erosion protection	Temporary	SLS1	25y no CC	Normal depth	4.0	Not required for culvert			
16. Hydraulic loading / setting soffit level	Temporary	ULS	500y no CC	100y no SLR	4.2			No piers	
17. Setting soffit level	Temporary	ULS	100y no CC	500y no SLR	4.6				

1.7 Navola Bridge

Bridge Priority:	Priority 1	**Name:**	Navola Bridge
Road:	Queens Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed
Design bridge soffit level:	5.0 mRL	**Design bridge deck level:**	6.2 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Monica Hoetjes	**Reviewer:**	Cameron Oliver
Model software/type:	HEC-RAS 2D model	**Latest model review date:**	15 November 2023

Comments:

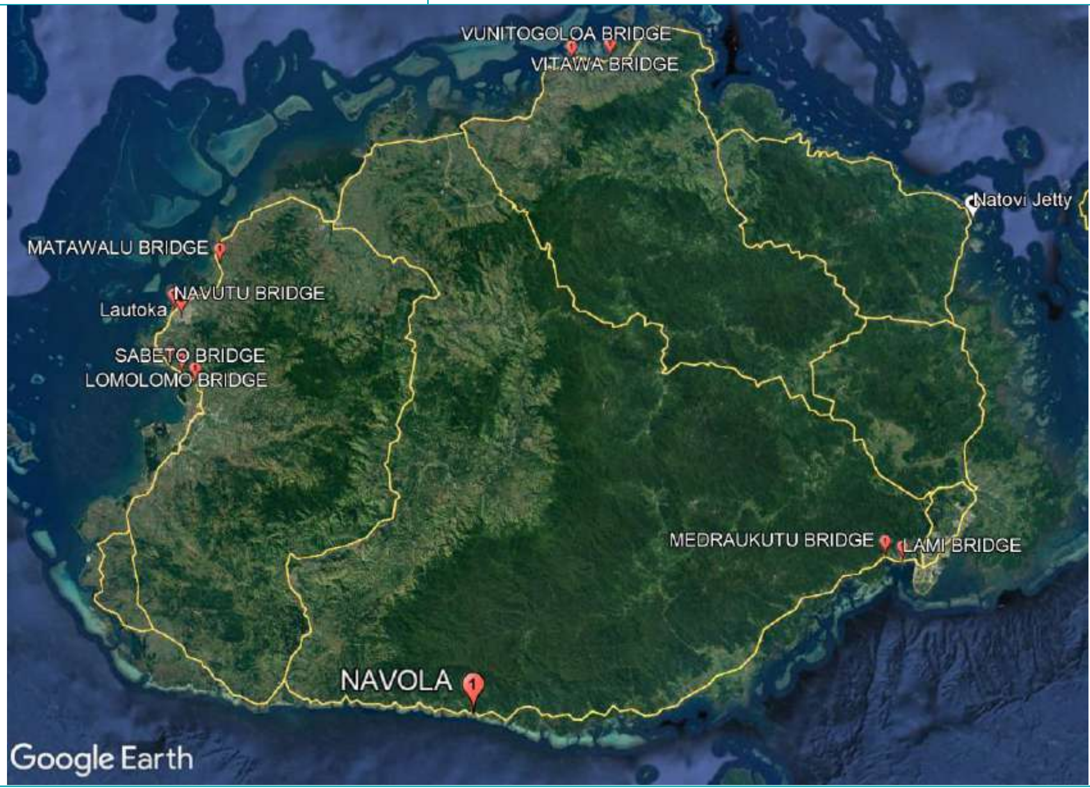
Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. However, this is an accepted limitation of the modelling and the terrains created are the best with the information available.

Note, compound bridge piers with debris rafts have been modelled as uniform piers with an effective width (for the design bridge only), due to a limitation in the modelling software.

The Shallow Water Equation set, Eulerian-Lagrangian Method (SWE-ELM) was applied to the model.

As the road crosses the stream, it is rising from west to east where the road is cut into a bluff. As such, the bridge level is higher than required to meet Design Criteria requirements for freeboard.

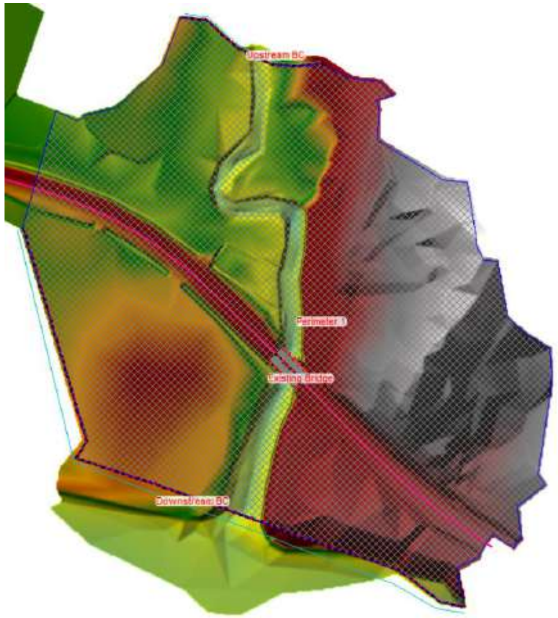
This model and results are not to be used for other purposes.



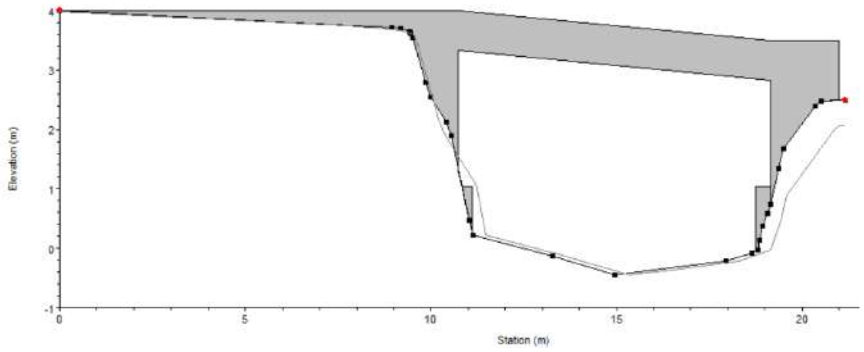
1.6.1 Existing Bridge

Navola bridge aerial

From downstream elevation (FRA, 2016)

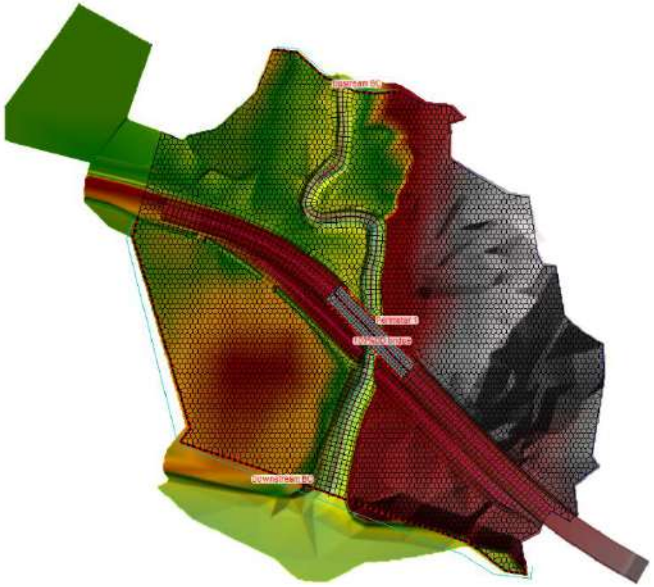


Existing bridge HEC-RAS model layout

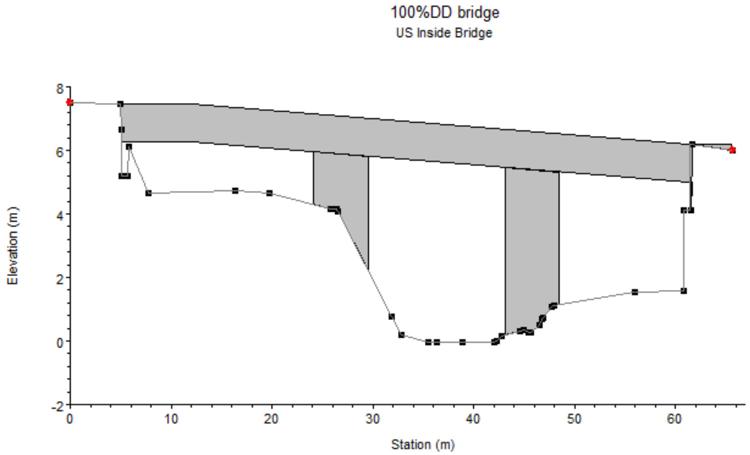


Existing bridge geometry

1.6.2 Design Bridge



Design bridge HEC-RAS model layout



Design bridge geometry

1.6.3 Temporary Bridge

No temporary bridge has been modelled for this location.

1.6.4 Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	3.6				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	3.6				
3. Sensitivity for setting soffit level	Sensitivity	SLS2	100y +40%CC	20y + 1.09m SLR	3.9				
4. Sensitivity for setting soffit level	Sensitivity	SLS2	25y +40%CC	100y + 1.09m SLR	Not reported. WSE < Run 3				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	3.6	1.1	3.8		
6. Sensitivity for erosion protection	Sensitivity	SLS2	100y +40%CC	Normal depth		1.1	4.0		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	3.9			1.0	1.8
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	3.8				
9. Sensitivity for hydraulic loading / setting soffit level	Sensitivity	ULS	1000y +40% CC	100y +1.09m SLR	4.2			1.0	1.8
10. Sensitivity for setting soffit level	Sensitivity	ULS	100y +40% CC	1000y +1.09m SLR	Not reported. WSE < Run 9				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	3.9				1.9
12. Sensitivity for hydraulic loading	Sensitivity	ULS	1000y +40%CC	Normal depth	4.1				1.9

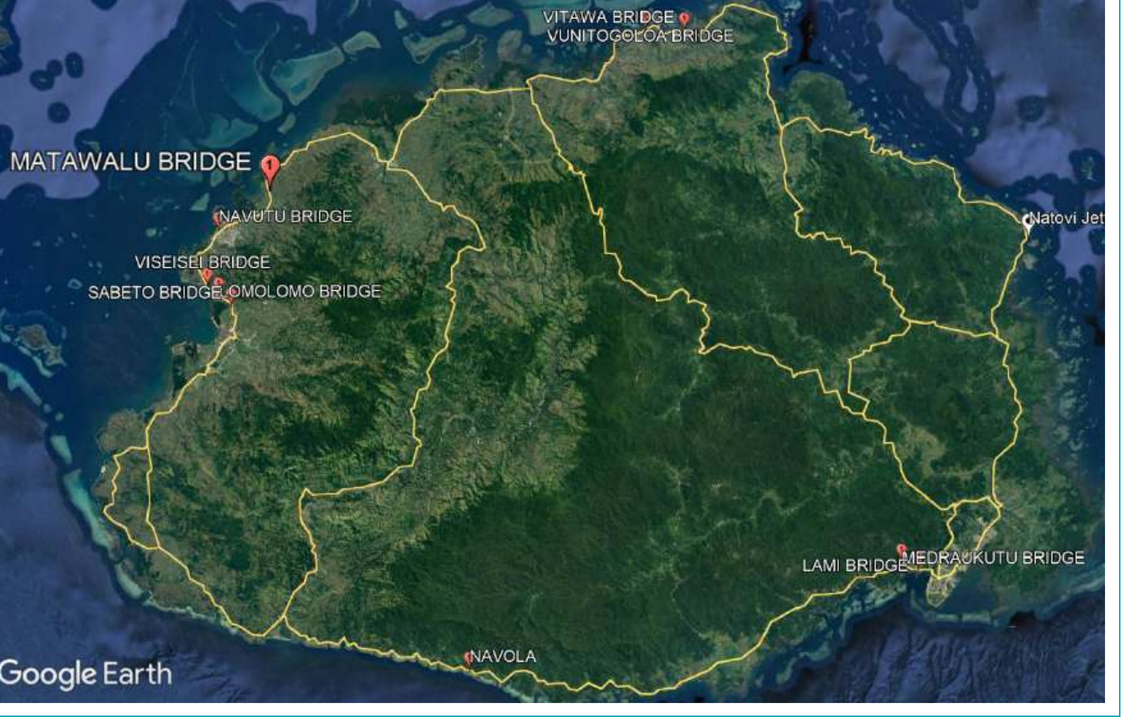
Matawalu Bridge

Bridge Priority:	Priority 1	**Name:**	Matawalu Bridge
Road:	Kings Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	5.5 mRL	**Design bridge deck level:**	6.7 mRL
Temporary bridge soffit level:	4.9 mRL	**Temporary bridge deck level:**	5.8 mRL
Modeller:	Hans Ching	**Reviewer:**	Michael Law
Model software/type:	HEC-RAS 2D model	**Initial model review date:**	18 December 2023

Comments:

Due to the absence of LiDAR/survey covering a wider area, the extent of the modelled terrain is limited. While this is an accepted limitation of the modelling and the terrains created are the best with the information available, it is conservative as it assumes all the design flow for the catchment passes through/via the bridge. In the larger floodplains such as Matawaluo, this ignores the potential for floodwaters to be conveyed on the wider (unsurveyed) floodplain and assumes ‘glass-walling’ at the edge of the modelled extents. All other things being equal, this approach will generate modelled flood levels that are higher than would occur.

To moderate the conservativism of a model using limited survey extent with significant glass walling, we can estimate the flow passing through our surveyed modelled extent by using a simple 2D model of the wider area based on a satellite-captured digital elevation model (Copernicus GLO-30) with a 30 m horizontal resolution DEM grid. This doesn’t provide the detail required for accurate modelling, but it can be used to identify significant overland flow paths that divert water away from the detailed model area.



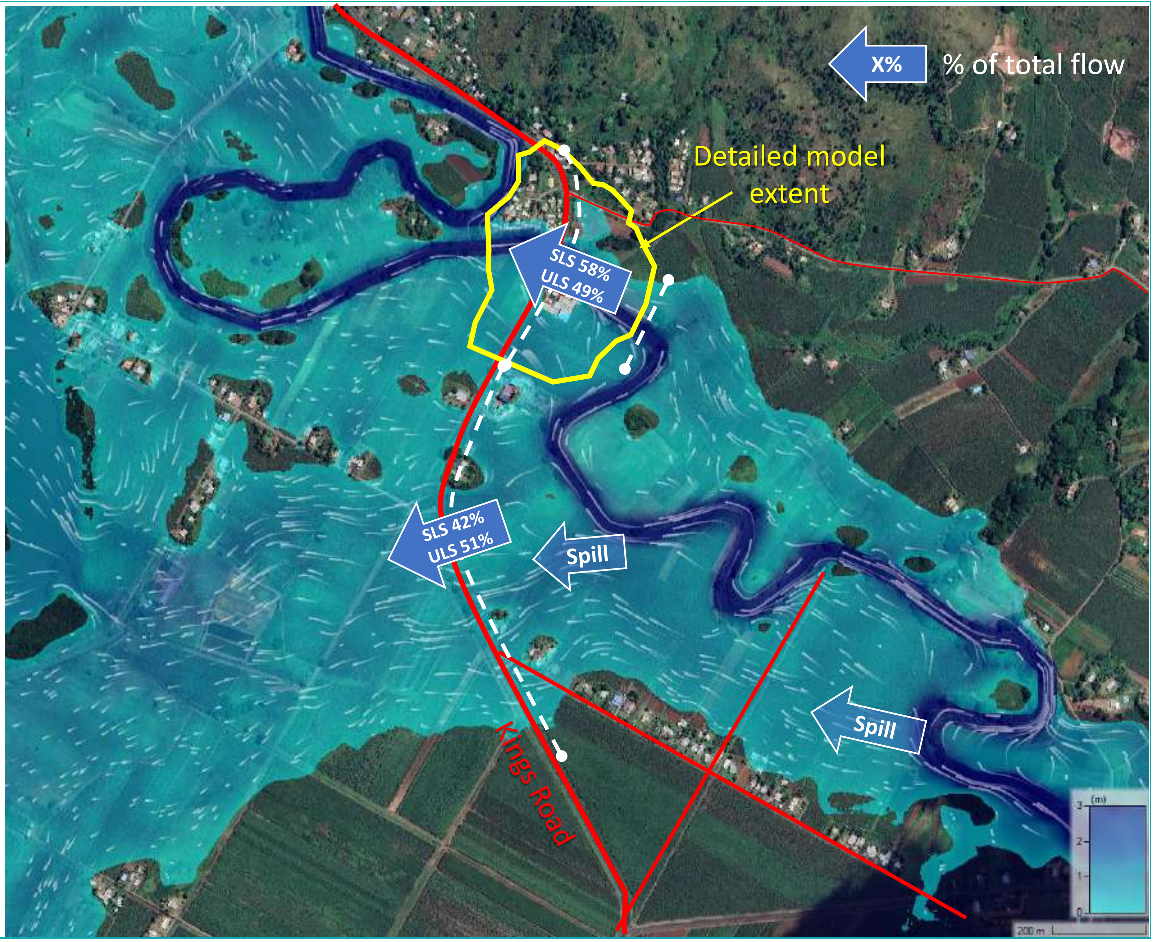
In the case of Matawalu, using the 30 m DEM indicates (See diagram) that water will spill out of the river about 1-2 km upstream of the bridge, with about 42% of the total river bypassing to the south of the bridge (outside of our modelled area) in the SLS2 event and 51% in the ULS event.

Though approximate, this suggests that only 58% of the flow passes through the small extent of the detailed model in the SLS2 event and 49% in the ULS event. This reduces modelled flood levels at the bridge.

The peak water levels for the SLS2 and ULS events occur with normal depth (ND) downstream flow conditions rather than with the downstream water level set based on extreme event sea levels.

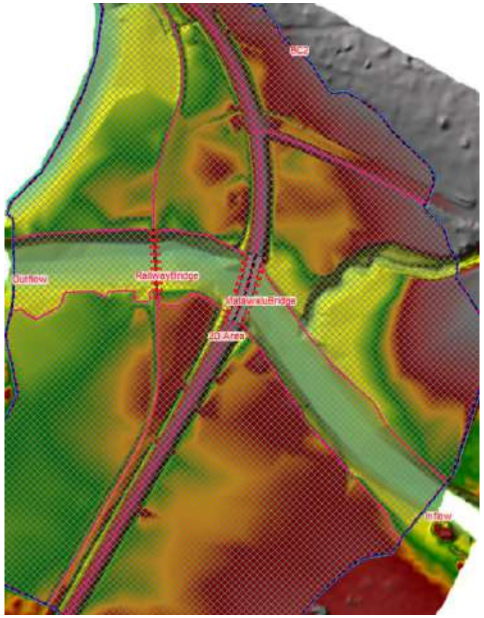
Note, compound bridge piers with debris rafts have been modelled as uniform piers with an effective width (for the design bridge only), due to a limitation in the modelling software.

The Shallow Water Equation set, Eulerian-Lagrangian Method (SWE-ELM) was applied to the model.



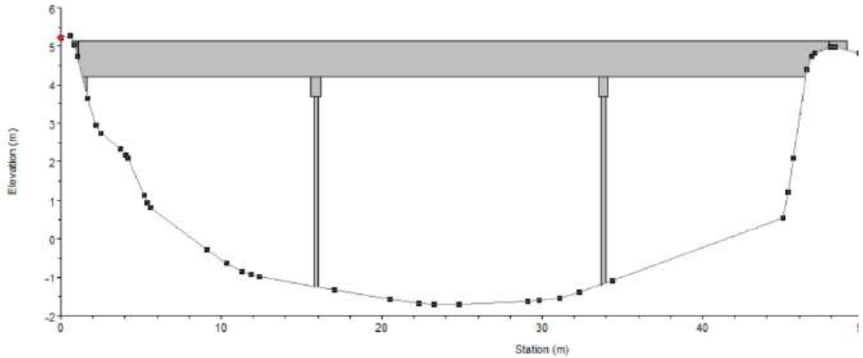
Existing Bridge

Matawalu bridge aerial



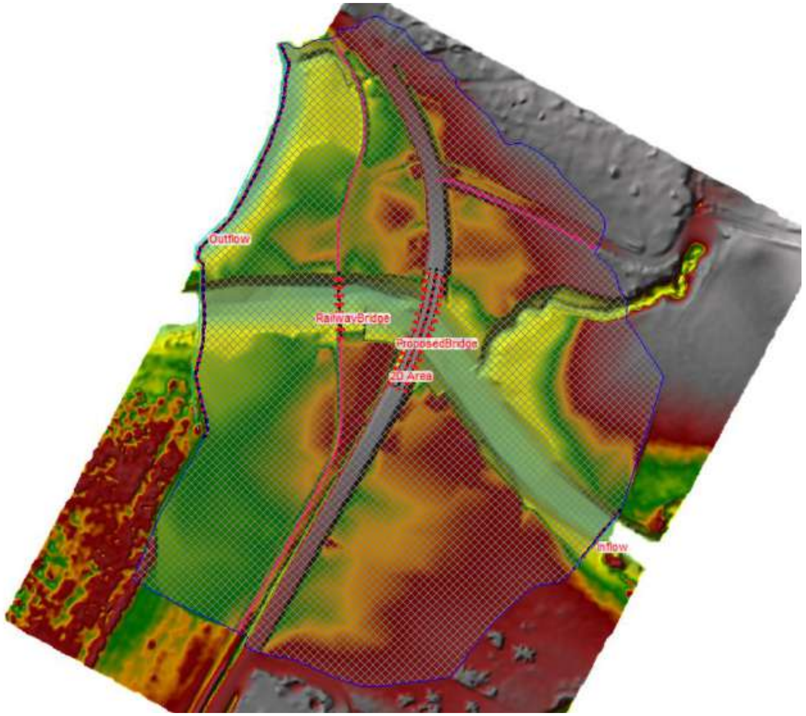
Existing bridge HEC-RAS model layout

From downstream elevation (FRA, 2016)

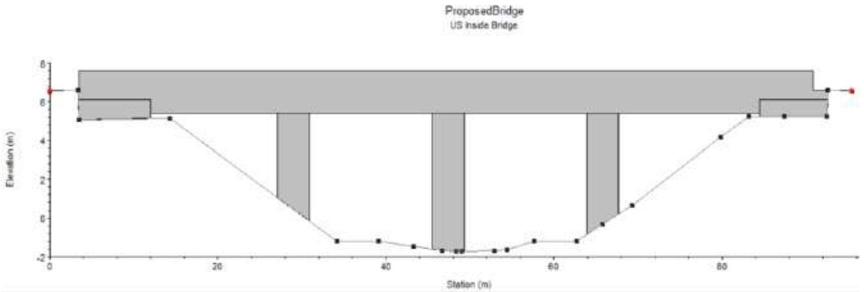


Existing bridge geometry

Design Bridge

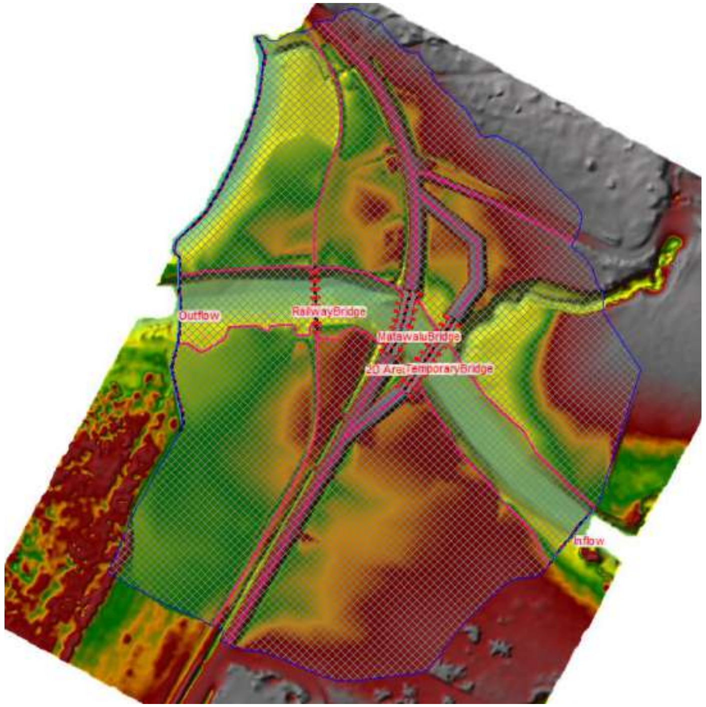


Design bridge HEC-RAS model layout

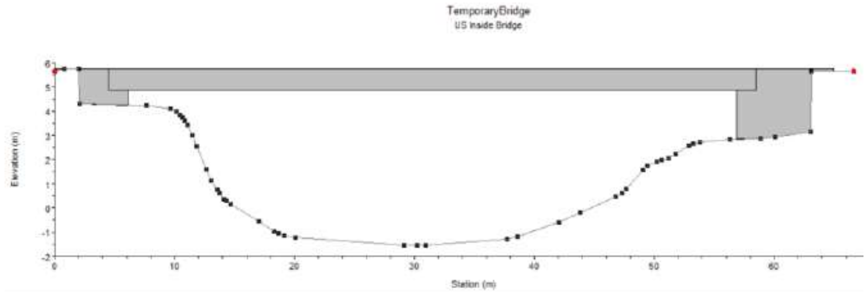


Design bridge geometry

Temporary Bridge



Temporary bridge HEC-RAS model layout



Temporary bridge geometry

Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	3.80 (lower than ND level)				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	3.70 (lower than ND level)				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	4.60				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	Not reported. WSE < Run 4				
5. Erosion protection & soffit level setting	Design	SLS2	100y +10%CC	Normal depth	4.30	3.20	6.10		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		2.70	6.70		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	4.50 (lower than ND level)			3.50	2.70
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	4.50 (lower than ND level)				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	5.10			3.90	2.90
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	Not reported, WSE < Run 10				
11. Hydraulic loading & soffit level setting	Design	ULS	1000y +10%CC	Normal depth	4.70				2.50
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	5.10				2.80
13. Setting soffit level	Temp.	SLS1	25y no CC	10y no SLR	2.90				
14. Setting soffit level	Temp.	SLS1	10y no CC	20y no SLR	Not reported, WSE < Run 13				
15. Erosion protection	Temp.	SLS1	25y no CC	Normal depth	3.30	1.6	4.8		
16. Hydraulic loading / setting soffit level	Temp.	ULS	500y no CC	100y no SLR	3.90			No piers	2.80
17. Setting soffit level	Temp.	ULS	100y no CC	500y no SLR	Not reported, WSE < Run 16				

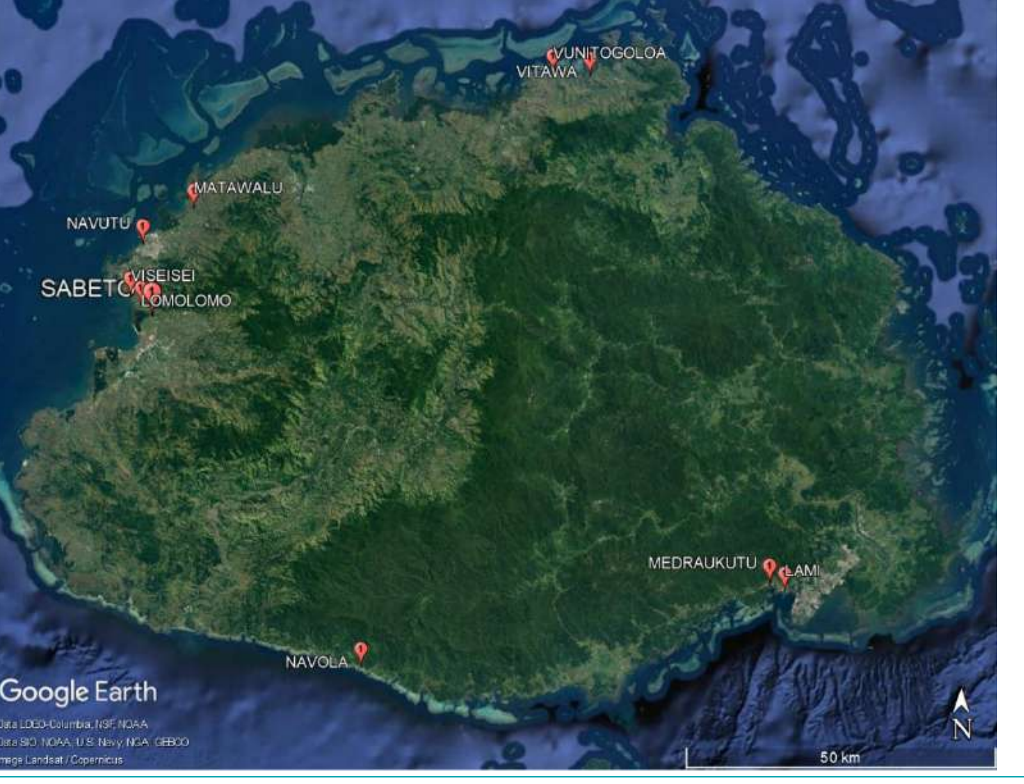
Bridge Priority:	Priority 1	**Name:**	Sabeto Bridge
Road:	Queens Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	5.05 mRL	**Design bridge deck level:**	6.15 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Hans Ching / Monica Hoetjes	**Reviewer:**	Michael Law
Model software/type:	HEC-RAS 2D model	**Latest model review date:**	12 October 2023

Comments:

In line with the modelling approach used for the other bridges through (and as presented for external review in February 2023), the flood model was based on survey covering a small area of the river and floodplain due to the absence of LiDAR/survey covering a wider area, and the Diffusion Wave (DW) equation set was used. The catchment design flow was routed through the limited model extent. While this could increase design flood levels, use of DW equations could be expected to reduce flood levels compared to use of the more detailed Shallow Water Equations (SWE)

The design water levels and velocities are based on these model results for reasons explained below.

In July 2023, the External Reviewer commented that the SWE should be used to provide better definition of water levels around the bridge and that this would include better representation of the effects of momentum, especially super-elevation of water levels around the outside of the bend upstream of the bridge.



Use of the SWE Eulerian-Lagrangian Method (SWE-ELM) with no change to the model extent or design flow results in a material increase in average flood levels immediately upstream of the bridge of about 200-300 mm, but with bigger increases at the southern abutment on the outside of the bend; there being 400-500 mm difference in modelled water levels between the inside and outside bends of the river at the bridge.

Use of SWE-ELM compounds a conservative approach to the flood modelling, that assumes all the design flow for the catchment passes through/via the bridge and area of the limited survey extent. In the larger floodplains such as Sabeto, this ignores the potential for floodwaters to be conveyed on the wider (unsurveyed) floodplain and assumes 'glass-walling' at the edge of the modelled extents. All other things being equal, this approach will generate modelled flood levels that are higher than would occur.

To moderate the conservativism of a model using limited survey extent with significant glass walling and the SWE set the model extent should be revisited. Without detailed survey/DEM of the whole floodplain/valley, this is not possible to do in any detail. However, we can estimate the flow passing through our surveyed modelled extent by using a simple 2D model of the wider area based on a satellite-captured digital elevation model (Copernicus GLO-30) with a 30 m horizontal resolution DEM grid. This doesn't provide the detail required for accurate modelling, but it can be used to identify significant overland flow paths that divert water away from the detailed model area.

In the case of Sabeto, using the 30 m DEM indicates (See diagram on following page) that water will spill out of the river about 600m upstream of the bridge, with 30%-40% of the total river bypassing to the south of the bridge (outside of our modelled area), while about 10% of the flow bypasses to the north.

Though approximate, this suggests that only 50%-60% of the flow passes through the small extent of the detailed model, which would reduce modelled flood levels at the bridge.

A check of the SWE model results indicates that the SLS and ULS design flood levels (based on the DW model runs) are achieved with about 80% of the total design flow. This is more than the 50% estimated from the 30 m grid model and so the DW-based design levels are likely to be conservative.

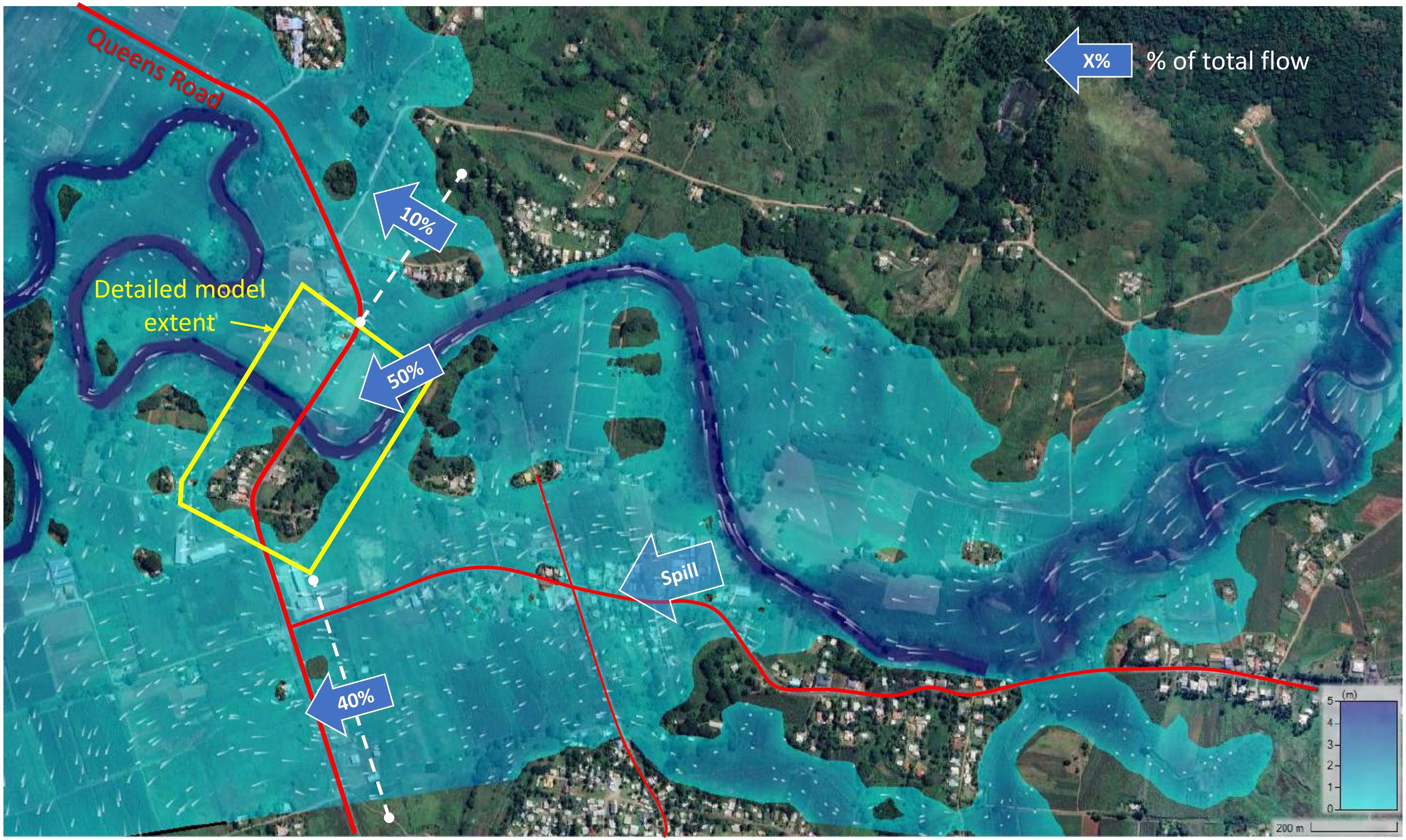
Given the uncertainty over how much flow bypasses the modelled area, it is prudent to retain the flood levels used to set the bridge level despite these being based on conveying the full flow through the detailed model area and using the Diffusion Wave equation set.

Note, compound bridge piers with debris rafts have been modelled as uniform piers with an effective width (for the design bridge only), due to a limitation in the modelling software.

The existing bridge was omitted from the permanent bridge model, though the bridge is to be retained. So, we have done additional HEC-RAS model runs to test the impact of the existing bridge on the model results. These additional model runs were undertaken using the SWE equation set, with the reduced design flow. Under these model conditions, when the existing bridge was included, the resulting modelled upstream water levels increased by less than 50 mm (SLS2 and ULS river-dominated runs) when compared to the SWE reduced flow model runs without the existing bridge. With the existing bridge included, water velocity decreased slightly at most places along the channel banks and at upstream of the permanent bridge piers.

However, the adopted diffusion wave model results, that are reported in the design report and Appendix C, result in flood levels that are still higher than these SWE test runs that include the existing bridge. Hence, inclusion or omission of the existing bridge does not change the reported hydraulic model results.

This model and results are not to be used for other purposes.


Queens Road
X%
% of total flow
10%
Detailed model extent
50%
Spill
40%
(m)
5
4
3
2
1
0
200 m

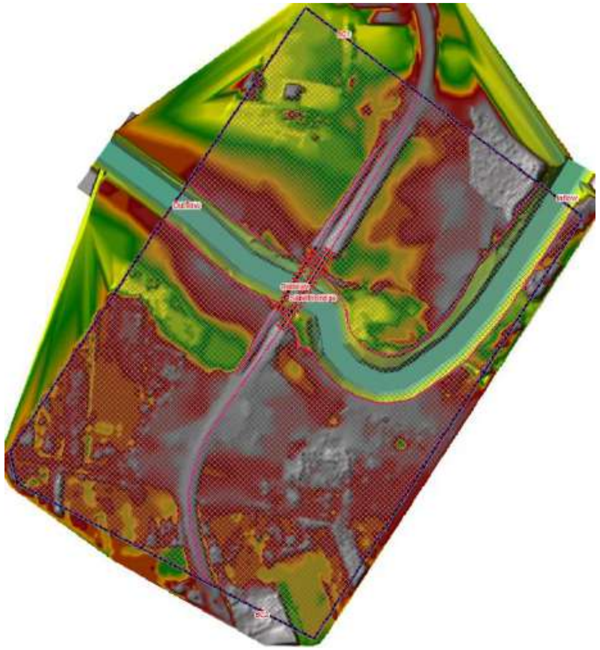
Beca

Sabeto Bridge

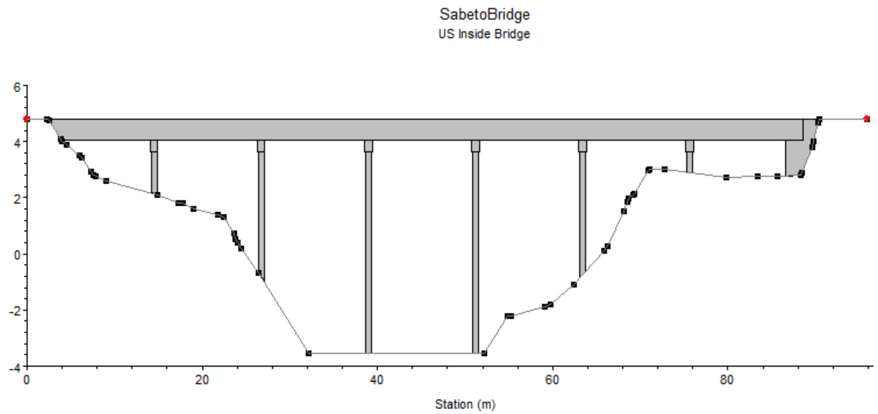
Existing Bridge

Sabeto bridge aerial

From upstream elevation (FRA, 2016)

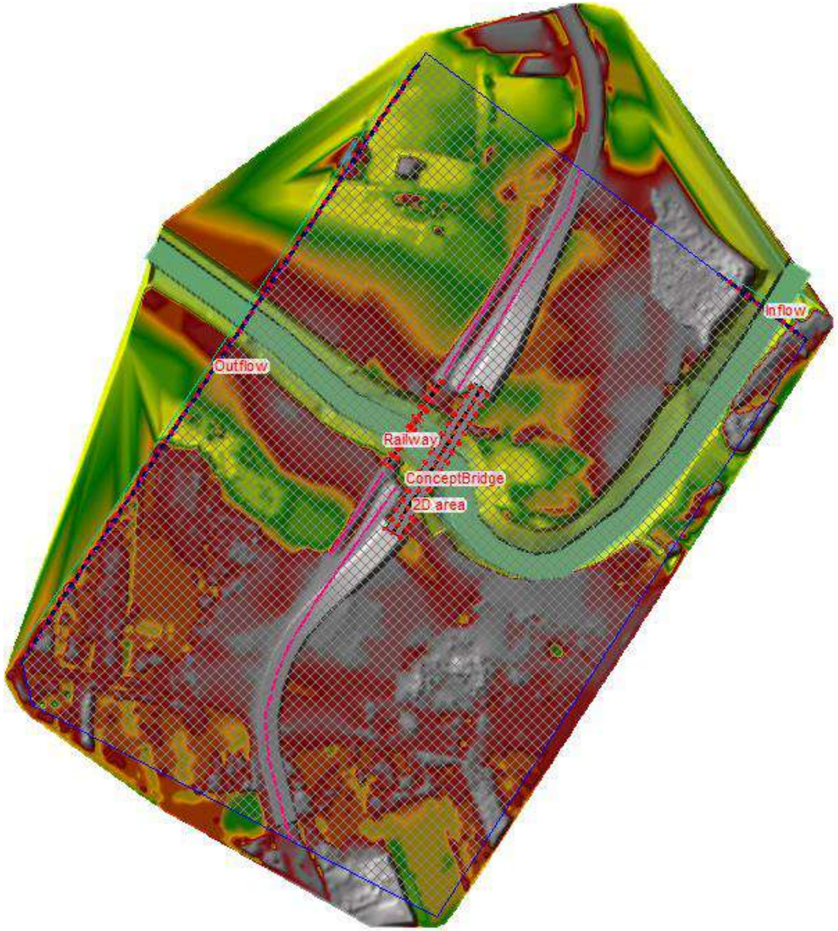


Existing bridge HEC-RAS model layout



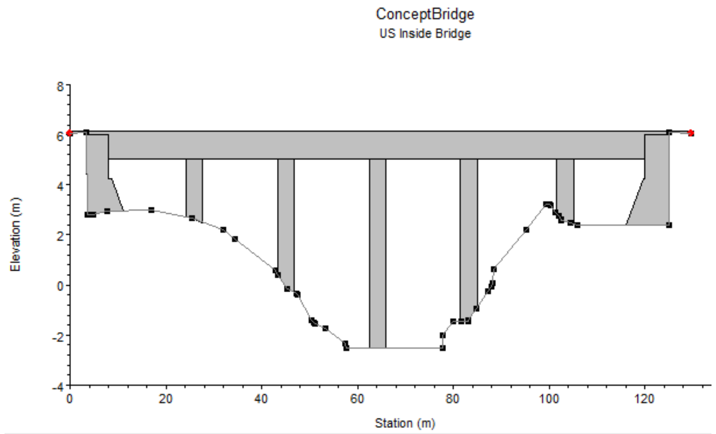
Existing bridge geometry

Design Bridge



Design bridge HEC-RAS model layout

N.B. The image does not show retention of the existing bridge, as this was not included in the DW 'full flow' model runs used for design, as they resulted in higher water levels than the sensitivity model runs using SWE equations and educed(factored) flows. See notes above.



Design bridge geometry (with pier widths increased to represent equivalent pier width due to debris)

1.9.1 Temporary Bridge

No temporary bridge has been modelled for this location.

Results – Diffusion Wave (full flow)

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Approach velocity on piers (m/s)	Approach velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	3.8				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	3.3				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	4.1				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	Not reported, WSE < Run 3				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	4.1	4.3	6.6		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		4.5	6.9		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	4.2			3.9	4.3
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	4.2				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	4.6			4.0	4.5
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	4.6				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	4.5				3.4
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	4.9				3.5

Note that the results reported are those used for design and are outputs from the Diffusion Wave model runs (80% Detailed…) with the total design flow routed through the detailed model area. These results are slightly higher than those generated using the SWE-ELM equation set and the estimated reduced flow at the bridge, but have been adopted as a precautionary approach based on the uncertainty around the flow splits estimated from the coarse 30m grid wider-catchment model

Lomolomo Bridge

Bridge Priority:	Priority 1	**Name:**	Lomolomo Bridge
Road:	Queens Road	**Island:**	Viti Levu
Importance level (IL):	3	**Design stage**	100% Detailed Design
Design bridge soffit level:	2.3 mRL	**Design bridge deck level:**	3.5 mRL
Temporary bridge soffit level:	N/A	**Temporary bridge deck level:**	N/A
Modeller:	Monica Hoetjes	**Reviewer:**	Michael Law
Model software/type:	HEC-RAS 2D model	**Model review date:**	15 February 2024

Comments:

Due to the limited survey extent across the Lomolomo Bridge floodplain, the modelled terrain has been extended using a satellite-captured digital elevation model (DEM) with a 30 m grid (Copernicus GLO-30). Use of the 30 m DEM improves the representation of how much flow reaches the bridge, and therefore improves the confidence in the flood model results.

Note that the design bridge shown in the hydraulic assessment summary sheet is an initial design modelled to inform detailed design, and so may differ from the current detailed design bridge due to refinement of the detailed design. These design differences would not cause a material difference to the model results, and these model results are still valid.

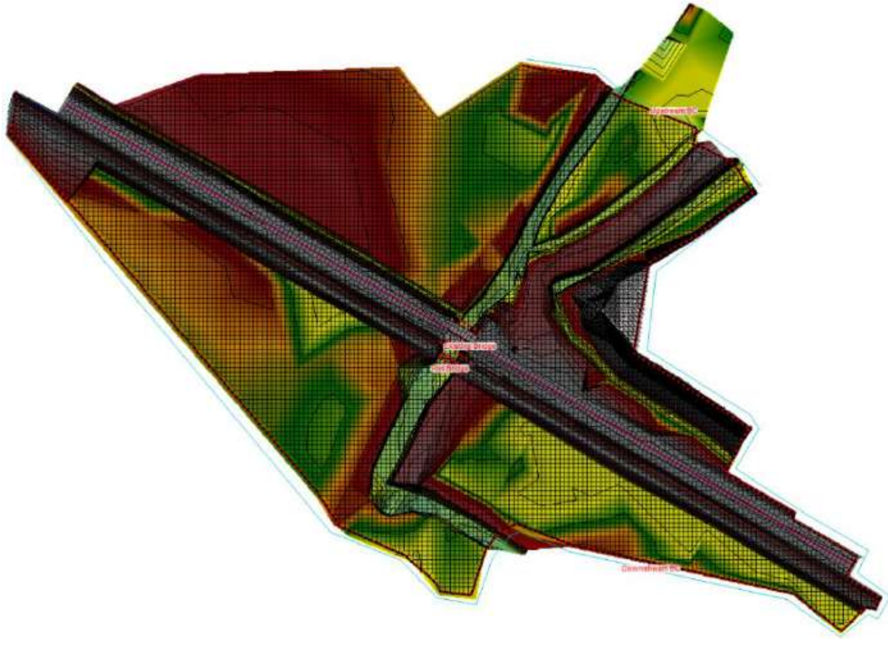
Note, the bridge pier with debris raft has been modelled as a uniform pier with an effective width, due to a limitation in the modelling software.

The Shallow Water Equation set, Eulerian-Lagrangian Method (SWE-ELM) was applied to the model. This model and results are not to be used for other purposes.

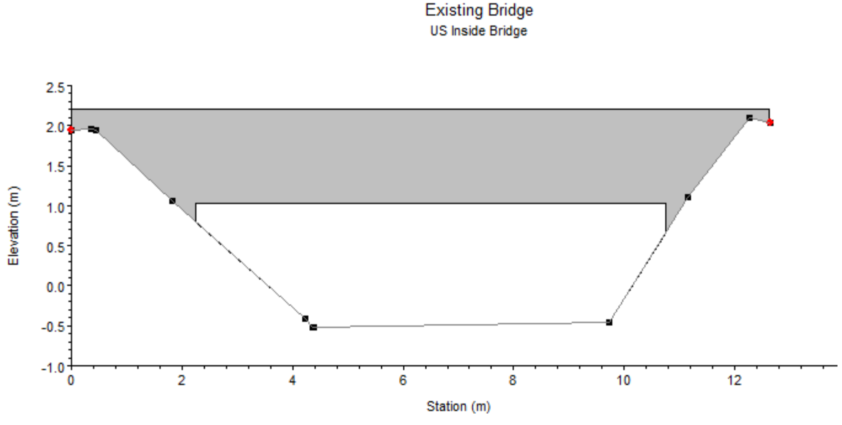
Existing Bridge

Lomolomo bridge aerial

From upstream elevation (FRA, 2016)

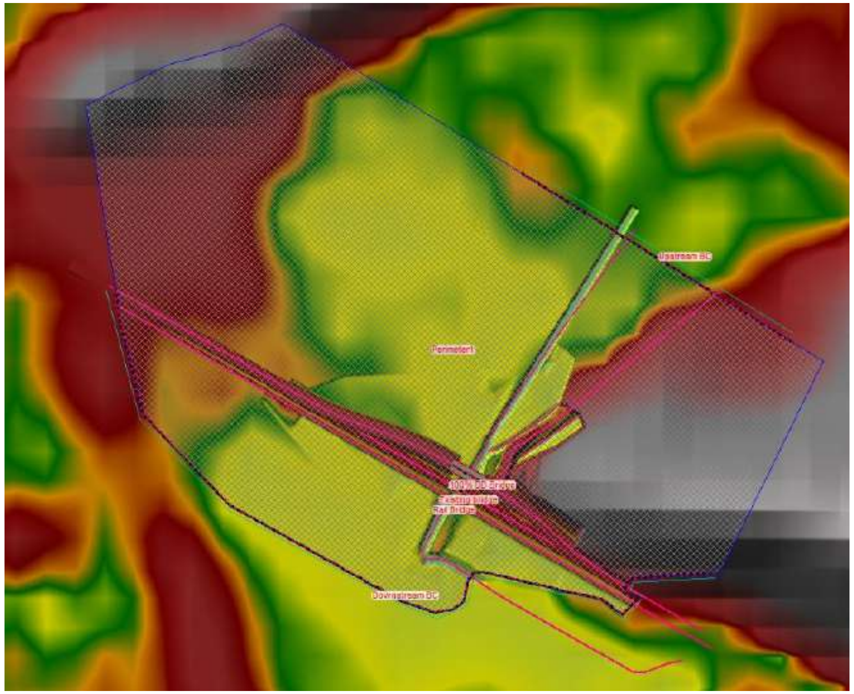


Existing bridge HEC-RAS model layout

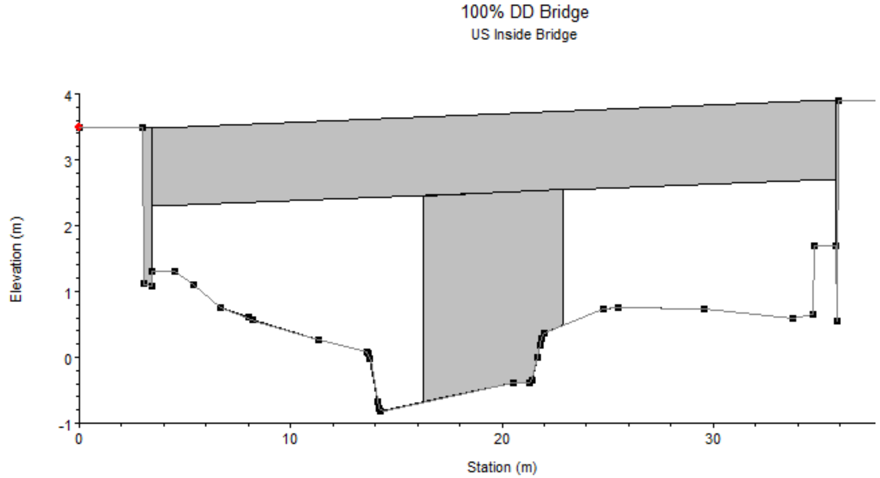


Existing bridge geometry

Design Bridge



Design bridge HEC-RAS model layout (includes extension using 30 m grid DEM)



Design bridge geometry

Temporary Bridge

No temporary bridge has been modelled for this location.

Model Results

Purpose	Bridge	Rainfall event	Flow event	Tide level	WSE on U/S face of bridge (mRL)	Velocity on banks (m/s)	Channel depth (m)	Velocity on piers (m/s)	Velocity on superstructure (m/s)
1. Setting soffit level	Design	SLS2	100y + 10%CC	20y + 0.73m SLR	3.2				
2. Setting soffit level	Design	SLS2	25y + 10%CC	100y + 0.73m SLR	3.1				
3. Sensitivity for setting soffit level	Design	SLS2	100y +40%CC	20y + 1.09m SLR	Not reported, WSE < Run 4				
4. Sensitivity for setting soffit level	Design	SLS2	25y +40%CC	100y + 1.09m SLR	3.4				
5. Erosion protection	Design	SLS2	100y +10%CC	Normal depth	3.1	2.1	3.9		
6. Sensitivity for erosion protection	Design	SLS2	100y +40%CC	Normal depth		2.3	4.1		
7. Hydraulic loading / setting soffit level	Design	ULS	1000y +10%CC	100y +0.73m SLR	3.3			1.0	0.7
8. Setting soffit level	Design	ULS	100y +10%CC	1000y +0.73m SLR	4.1				
9. Sensitivity for hydraulic loading / setting soffit level	Design	ULS	1000y +40% CC	100y +1.09m SLR	Not reported, WSE < Run 10			0.7	0.5
10. Sensitivity for setting soffit level	Design	ULS	100y +40% CC	1000y +1.09m SLR	4.4				
11. Hydraulic loading	Design	ULS	1000y +10%CC	Normal depth	3.3				1.1
12. Sensitivity for hydraulic loading	Design	ULS	1000y +40%CC	Normal depth	3.4				1.1