Inception and Stakeholders Consultation Report

Review and Updating of the Vanuatu Rural Road Design Guide

Sustainable, transformative and resilient for a Blue Pacific

Review and Updating of the Vanuatu Rural Road Design Guide (2017)

Inception and Stakeholder Consultation Report
Deliverable 1a

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SPREP
Secretariat of the Pacific Regional Environment Programme

Contract

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Disclaimer

Robert Hardy
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1. INTRODUCTION

1.1 SPREP

The Secretariat of the Pacific Regional Environment Programme (SPREP) is the regional organisation established by the Governments and Administrations of the Pacific charged with protecting and managing the environment and natural resources of the Pacific. The head office is based in Apia, Samoa with over 100 staff. There are SPREP offices in Fiji, Republic of the Marshall Islands and Vanuatu as well as SPREP Officers stationed in the Solomon Islands.

The establishment of SPREP in 1993 sent a clear signal to the global community of the deep commitment of Pacific Island Governments and Administrations for better management of the environment within the context of sustainable development.

The strategic direction for SPREP is clearly set out in the 2017-2026 SPREP Strategic Plan. This Plan outlines the mandate, vision and programmes for the organisation, and places strong emphasis on effective delivery of services to SPREP member countries and territories. SPREP's mandate is to promote cooperation in the Pacific region and provide assistance to Pacific Island Countries and Territories to protect and improve its environment and to ensure sustainable development for present and future generations.

SPREP is an accredited entity to the Grean Climate Fund (GCF) and the Adaptation Fund (AF), and an executing entity to the Global Environment Facility (GEF).

SPREP's Regional Goals are as follows:

- **Regional Goal 1:** Pacific people benefit from strengthened resilience to climate change;
- **Regional Goal 2:** Pacific people benefit from healthy and resilient island and ocean ecosystems;
- **Regional Goal 3:** Pacific people benefit from improved waste management and pollution control;
- **Regional Goal 4:** Pacific people and their environment benefit from commitment to and best practice of environmental governance.

1.2 Project Objectives

SPREP is the Implementing and Executing Entity for the GCF's Climate Information Services for Resilient Development in Vanuatu Project, known as Van-KIRAP.

As part of this project work, SPREP, working together with Vanuatu's Public Works Department (PWD) within its Ministry of Infrastructure and Public Utilities (MIPU) identified a need to review and update the existing Vanuatu Rural Road Design Guide which was produced under DFAT's Roads for Development (R4D) program in 2017. The key need is to adjust the design guidance to incorporate improved resilience of road infrastructure to the impacts of increasingly severe climate events.

Upon commencement of the services, the four key objectives of the consultancy services were described as follows:

1. Identification of the current gap in the existing design guides in terms of climate resilience and setting the scope of the review and updating through consultations with key stakeholders;

2. Conduct, review, evaluate and provide recommendations on updating the documents by mainstreaming climate change considerations;
3. Updating the Design Guide with recommendations on implementation procedures, and
4. Internalization of the updated documents in PWD and external stakeholders through orientation and training.

Through early stakeholder consultations held with PWD and Roads for Development 2 (R4D2) staff it has become evident that two further objectives should be added to the project. These are:

5. Simplify and improve the useability of Vanuatu's Road Design Guidance by focusing on articulation of clear design requirements rather than detailed and lengthy explanations of the rationale for various design solutions[1], and
6. Develop Road Design Guidance to complement and integrate with other recent or emerging PWD policies and guides, including the Public Roads Strategy (yet to be formally adopted but available in draft form), latest PWD Business Plan and associated Work Plans, Quality Control Manual (developed through the World Bank's VIRIP project) and the Contract Administration Manual (also developed through VIRIP)[2].

1.3 Rationale for the Project

On 20 March 2023, the Intergovernmental Panel on Climate Change (IPCC) published its AR6 Synthesis Report which makes plain the urgent need to address the escalating climate crisis. As would be expected, the report urges governments and leaders to take urgent, deep mitigation action to reduce CO_2e emissions. However, the report also recognises the need to focus on resilience of assets and systems as indicated in the following paragraphs:

> ***Paragraph C.1.1:*** *Evidence of observed adverse impacts and related losses and damages, projected risks, levels and trends in vulnerability and adaptation limits, demonstrate that* ***worldwide climate resilient development action is more urgent than previously assessed*** *in [Report] AR5. Climate resilient development integrates adaptation and GHG mitigation to advance sustainable development for all. Climate resilient development pathways have been constrained by past development, emissions and climate change and are progressively constrained by every increment of warming, in particular beyond 1.5°C.*
>
> ***Paragraph C.5****: Prioritising equity, climate justice, social justice, inclusion and just transition processes can enable adaptation and ambitious mitigation actions and climate resilient development. Adaptation outcomes are enhanced by increased support to regions and people with the highest vulnerability to climatic hazards.* ***Integrating climate adaptation into social protection programs improves resilience.*** *Many options are available for reducing emission-intensive consumption, including through behavioural and lifestyle changes, with co-benefits for societal well-being.*
>
> ***Paragraph C.6:*** *Effective climate action is enabled by political commitment, well-aligned multilevel governance, institutional frameworks, laws, policies and strategies and enhanced access to finance and technology. Clear goals, coordination across multiple policy domains,*

[1] Feedback suggested that the existing design guidance is not widely used by PWD staff because it reads like an academic thesis rather than providing simple, practical design guidance.
[2] Where appropriate, the updated road design guidance will make reference to these other documents.

and inclusive governance processes facilitate effective climate action. Regulatory and economic instruments can support deep emissions reductions and climate resilience if scaled up and applied widely. ***Climate resilient development benefits from drawing on diverse knowledge.***

Paragraph C.7.1: *Improved availability of and access to finance would enable accelerated climate action. Addressing needs and gaps and broadening equitable access to domestic and international finance, when combined with other supportive actions, can act as a catalyst for accelerating adaptation and mitigation, and enabling climate resilient development****. If climate goals are to be achieved, and to address rising risks and accelerate investments in emissions reductions, both adaptation and mitigation finance would need to increase many-fold.***

Against this global backdrop, it should be recognised that Vanuatu is among the most vulnerable countries on earth to the increasing impacts of climate change, including climate related natural disasters and the effects of slow-onset events such as the sea-level rise and ocean acidification. Of particular importance to road infrastructure in Vanuatu is the impact of tropical cyclones which create significant damage to roads, usually through the action of extremely strong water currents caused by heavy, prolonged rainfall. Most damage to road infrastructure is therefore caused at the intersection points between roads and water courses. Anecdotally, PWD engineers have confirmed that such cyclone-induced water damage to roads has steadily worsened in recent years. This suggests that current approaches to design and construction need to be updated to deal with the changing climatic conditions.

The Van-KIRAP project, funded by SPREP, aims to build technical capacity in Vanuatu to harness and manage available climate data; support enhanced coordination and dissemination of tailored information; and support the application of relevant Climate Information Services (CIS) through real-time development processes, for more resilient outcomes. The project has a focus on addressing information gaps and priority needs of target beneficiaries at national, provincial and local community levels across the five priority sectors: tourism; agriculture; infrastructure; water and fisheries.

The Van-KIRAP project will deliver:

- Enhanced capacity and capability of national development agents, to understand, access and apply CIS;
- Enhanced CIS communications, knowledge products, tools, and resources for practical application to development processes;
- Enhanced reliability, functionality, utility and timeliness of underlying CIS delivery systems and data collection infrastructure, and
- Enhanced scientific data, information and knowledge of past, present and future climate to facilitate innovated and resilient development.

It is important that road designers make best use of the improved local climate data which is being made available through the Van-KIRAP project. The road design guidance will therefore be updated to align with the new data available through Van-KIRAP.

The current road design guidance was created in 2017. Since that time, much has been learned about the likely climate change impacts as increasingly complex climate change modelling is undertaken. Also, PWD engineers, and those working on supporting programs to PWD, have had 6 years of experience of working with the 2017 Rural Road Design Guide and are therefore in a good position to be able to provide critical feedback on its effectiveness.

A simplified project logic is provided in Figure 1 below.

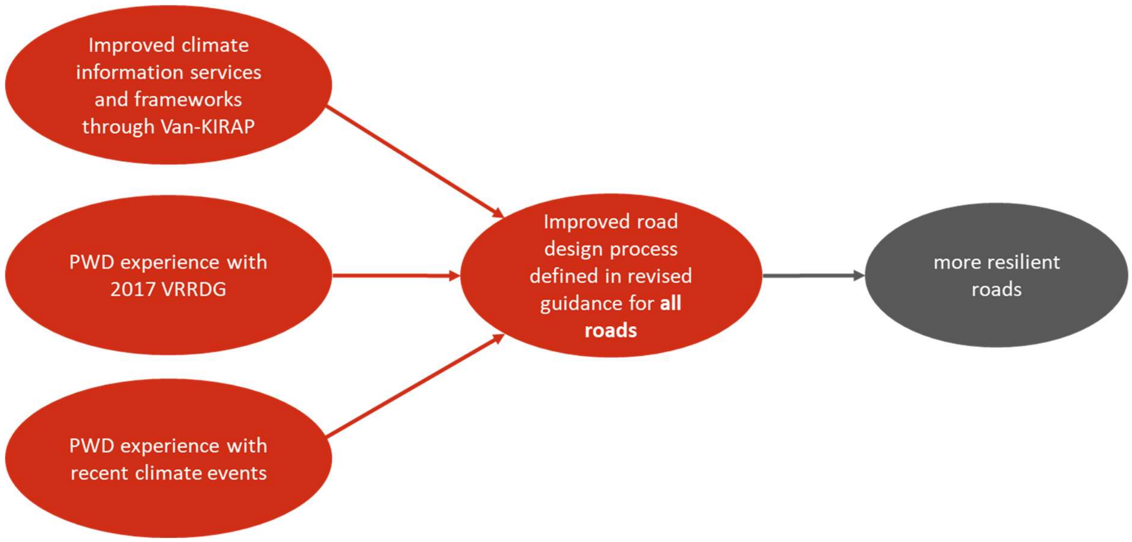

Figure 1: Simplified Project Logic

1.4 Vanuatu's Climate

Vanuatu's Meteorology and Geo-Hazards Department is an important source of local real-time climate data and information for the public, using local radio to disseminate information and warnings to the public leading up to an anticipated cyclone event.

The tropical cyclone season starts in November and runs until around April of the following year. Vanuatu typically receives around 2 or 3 cyclones during each cyclone season with the highest frequency usually in January and February. Historically, around 3 to 5 cyclones per decade have caused severe damage. Cyclones are notoriously complex and erratic in their movement making it difficult to predict their path and severity. Tropical cyclones can affect any of the islands of Vanuatu and can result in heavy rainfall, flash flooding, flooding of low-lying areas, coastal flooding, river flooding, storm surges, landslides, very rough seas and very strong winds. These events can cause a great deal of damage to assets and life. Recent Category 5 cyclones (based on the Australian tropical cyclone intensity scale) which made landfall in Vanuatu are listed in Annex C[3].

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[3] Source: https://en.wikipedia.org/wiki/List_of_Category_5_South_Pacific_severe_tropical_cyclones#:~:text=Severe%20Tropical%20Cyclone's%20Pam%2C%20Winston,devastation%20to%20Fiji%20and%20Vanuatu.

1.5 Vanuatu's Road Sector Challenges

Regardless of increasing climate change impacts, PWD already faces significant challenges in the construction and maintenance of roads across Vanuatu. These include:

Geography	Vanuatu is made up of many dispersed islands making the logistics of road construction and maintenance difficult, slow and costly.
Climate	Heavy rains and cyclones during the rainy season cause significant damage to Vanuatu's roads each year.
Materials	The local coronous gravels[4] generally available for road construction in Vanuatu are not ideal road-building materials compared to those in other countries.
Capacity	Vanuatu is a small nation with very few civil engineering graduates available to build up a competent and sustainable professional road sector.
Budget	The typical annual PWD roads budget is insufficient to maintain the existing 3,000km road network effectively and sustainably.
Planning	Planning of annual works within a constrained budget results in having to make difficult decisions between competing priorities (large islands vs small islands, core roads vs community/village links, new or upgraded roads vs maintenance, etc.)

The revised design guide for roads to be developed under this project must take into account the exceptional and unique set of challenges faced by Vanuatu.

[4] Coronous (or sometimes spelt coronus) gravels are those aggregates derived from coral. Such a broad grouping does not allow for the high degree of variability in deposits. The pavement-related properties of coronous deposits are primarily determined by the coral type, fragment shape, degree of recrystallisation and induration, degree of weathering and level of contamination by plastic fines. Coronous aggregates vary from being hard and equiaxed with a small proportion of plastic fines to being soft and flakey with a high level of clayey material.

2. MEETINGS AND STAKEHOLDER CONSULTATIONS

2.1 Kick-Off Meeting and Presentation

A kick-off meeting was held on 18 January 2023 Vanuatu time. A brief record of the meeting and the slides from the meeting are included in Annex A.

2.2 Consultation Background

Stakeholder Consultations have fallen into two broad groups:

- Consultations with operational PWD staff and supporting R4D2 staff on the existing Vanuatu Rural Road Design Guide and recent climate-change induced impacts on road assets, and
- Consultations with the Van-KIRAP team on available climate data, climate change forecasts and how these might be used to improve the resilience of roads through strengthened design.

The original intent for this project was to collect data and thoughts from PWD and R4D2 staff through a survey questionnaire, included as Annex B. Although this survey questionnaire was distributed in February 2023, PWD staff availability to provide responses was heavily impacted by PWD's need to respond urgently to a rare double cyclone event. Tropical Cyclone (TC) Judy made landfall in Vanuatu on 28 February followed by TC Kevin on 3 March. The cyclones contained destructive force winds with an average speed of 150 kph with peak gusts reaching up to 200 kph. Heavy rains, thunderstorms and rough seas accompanied these winds. Early government estimates suggested that 80% of Vanuatu's population was impacted by the two cyclones. The main provinces affected were the southern provinces of Tafea and Shefa, as shown in Figure 2, but the provinces of Malampa, Penama, Sanma and Torba were also affected.

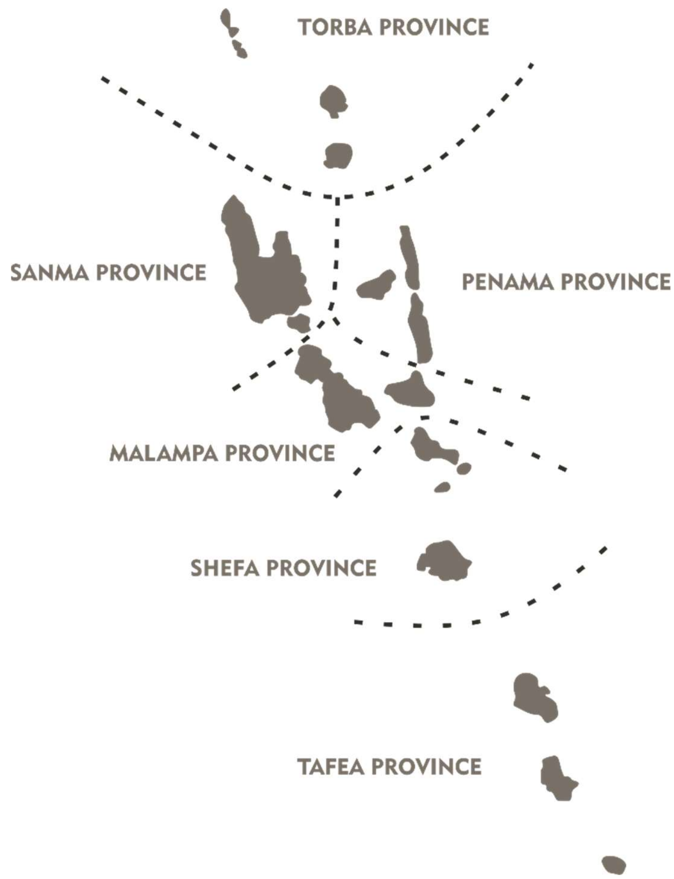


Figure 2: The Provinces of Vanuatu

Because of the understandable delays caused by this double cyclone event, the project approach was modified to include a series of online interviews which were structured around the survey questionnaire. Although the double cyclone event caused delays to the project, it has also provided valuable, recent information on the types of damage and modes of failure caused to road assets through extreme climate action. Many photographs of recent damage were provided by PWD staff and will be useful for inclusion in the new road design guide.

Table 1 below lists the consultation discussions and meetings held during the project inception phase.

Date	Interviewee	Position, Organisation
20 March 2023	Van-KIRAP team	-
2 May 2023	Harold Allanson	Project Engineer, PWD
3 May 2023	Ambatha Paraliu	Operations Manager, PWD
4 May 2023	Van-KIRAP team	-
4 May 2023	Chitra Thapa	Regional Operations Engineer, R4D2
9 May 2023	Nathan Tabi	Principal Engineer, PWD
10 May 2023	Morgan Ngwangko	Project Engineer, PWD
18 May 2023	Ben Roberts	Senior Engineering Advisor, R4D2

Table 1: List of Stakeholder Consultation Meetings

The project also received two completed survey questionnaires from Sanma and Torba Provinces, together with associated photographs of recently damaged roads.

2.3 Key Consultation Findings – PWD/R4D2

2.3.1 Findings in Relation to the Rural Roads Design Guide (2017) and Associated Documents

The key findings were as follows:

Use of 2017 VRRDG	Although PWD staff reported that the 2017 design guide is used occasionally, R4D staff suggested that its use was somewhat limited, and for most projects it is not used.
Relevance of design guide	PWD staff reported that, in reality, designs were already being upgraded compared to the requirements of the 2017 design guide. For instance 'armco' culverts were often replaced with box/slab culverts to increase capacity and resilience. As an example, this has occurred at numerous locations on Tanna. However, despite these upgrades, recent cyclones have caused damage to the roads around these box/slab culverts.
Ease of use of design guide	Almost all interviewees confirmed that the VRRDG was fairly easy to follow, understand and use. However, it is generally thought to contain too much background information on why certain design approaches are used rather than focusing on the steps to be followed to develop effective road designs. It was thought that some design processes, such as pavement design or culvert sizing, could be improved through the introduction of simplified design charts or tables. It was also noted that some key design tools were absent from the 2017 guide, such as rainfall Intensity-Duration-Frequency curves. These are referred to in the described design process but were not provided. In general terms, the design guide was considered to read like an academic report, rather than a useful design guide. It was also suggested that text could be reduced by cross-referencing other international design standards and guides where appropriate. Worked practical examples of how to apply design guidance would be a useful addition to the revised design guide.
Logical order of design guide	It was suggested that the design manual be adjusted to follow a natural design sequence so that it follows a step-by-step process, either set out as a flowchart or a table of logical steps. Section 5 on geometric standards was the most widely used part of the manual because it gave guidance on selecting the appropriate width of road for different traffic levels. This should probably be the starting point with any road design project.
Public Roads Strategy	MIPU have developed a draft Public Roads Strategy. Although this is not yet formally adopted by the Government of Vanuatu, it provides important guidance on how road works should be prioritised to ensure the core road network on each major island is maintained in good condition to provide all-weather connectivity. The improved design guidance will need to ensure that appropriate design solutions are applied to both core roads and non-core roads, with the resilience of core roads being given higher priority.
Urban roads	The current design guide covers only rural roads, but it was requested that the guidance be expanded to cover both rural and urban contexts. Only Port Vila and Luganville have roads which are classified as 'urban' but the reality is that many other small towns and townships have roads which carry out an urban function (such as carrying pedestrians,

providing parking, providing minibus stops, etc.) and these functions need to be taken into account during design regardless of the road's official classification. The intent is to provide a generalised design guide which can be applied to all roads.

Varied degrees of resilience	Interviewees accepted that some damage is likely to occur during every cyclone and that it was impossible to make all road assets completely resilient to cyclone impacts within reasonable cost constraints. The Public Roads Strategy sets out a policy of declaring a hierarchy of roads for each island (core roads and non-core roads) and it was suggested that differing degrees of resilience should be assigned to these two classes of road.
Surveys for design	It was acknowledged that design was often based upon insufficient survey information. Even basic topographic information was often unavailable to designers. However, PWD were undertaking a trial using drones with LIDAR cameras to generate an accurate digital surface model to aid improved design. This work is ongoing.
Lack of drainage design	From interviews it was evident that some roads were recently constructed or upgraded without due consideration of drainage as part of the design. When budgets are constrained, there is a tendency to prioritise expenditure on the road pavement (gravel, concrete, sealed) ahead of drainage, to the extent that some sections of road are constructed without any consideration of drainage at all[5]. Pavement should never be designed without due consideration of drainage.
Execution following design	Some interviewees suggested that the low resilience of roads stemmed more from a lack of attention to construction quality during execution of projects, rather than from a lack of attention to detailed design.
Road design guide training	Since the launch of the 2017 road design guide, except for some initial efforts, there has been little follow-on training in use of the road design guide for either PWD staff or supporting consultants/contractors. Without serious efforts to institutionalise the use of the design guide it has not been adopted as fully as it might have been. It is hoped the new design guide will address this by including a significant follow-on training component.
Use of Standard Specification for Roads and Bridges	Some PWD staff admitted that the standard specification was used as part of the documentation for development of tender packages, but beyond procurement was not referred to often[6]. It was accepted that different classes of contractor used the standard specification differently, with international contractors based in Port Vila much more likely to follow the detailed specification requirements, while local contractors found this more difficult because of a lack laboratory testing facilities and resources. The full specification contains descriptions of many construction elements, but only a few of these are regularly used in Vanuatu. A less daunting simplified specification which covers the key materials and elements of works might be useful. This may be created as a construction guide for Vanuatu rather than a technical specification or alternatively could be included as part of the revised design guide.

[5] This is a false economy because roads pavements which are designed without drainage will soon fail due to water action.
[6] For instance, it was accepted that the method for concrete mix design was not followed. Neither is regular strength testing of concrete undertaken. This leads to a significant risk of under-strength (and therefore less resilient) concrete.

Use of PWD Standard Drawings	The standard drawings are well presented and easy to understand. PWD reported that standard design drawings are useful but are usually adjusted for each project to suit local conditions. There was a consensus that the standard designs required upgrading to improve resilience. Also, larger R4D2-supported projects had generally developed project-specific drawings to suit local conditions and therefore made little use of the standard drawings. The standard drawings were not considered particularly useful for maintenance contracts as they only cover the initial construction of new works.
Standard drawing completeness	It was noted that the details included on some standard drawings were unclear. For example, details of double reinforcement required in larger complex structures was unclear on the current set of drawings. Bar bending schedules for many elements are not included and should be added.
Use of PWD Quality Control Manual & Contract Administration Manual	The World Bank's VIRIP program had developed two important manuals: (1) the Quality Control Manual (QCM), and (2) the Contract Administration Manual (CAM). These have been formally adopted for general use by PWD but are not widely used. The QCM was described as a very useful document as it includes all technical checklists required to effectively supervise construction works.

2.3.2 Findings in relation to the recent road performance during climate events were as follows:

Increased rainfall	Although anecdotal and without the benefit of detailed data, almost all PWD engineers reported that the increasing intensity of recent rains was causing much heavier storm flows if compared to previous years. Storms expected to be '1-in-50' year events were now occurring more frequently. It was also noted that the cyclone season appeared to be lengthening to include April.
Recent 2023 impacts	Most recent damage to roads caused by the 2023 cyclones (TC Judy and TC Kevin) had occurred in Tanna. Most damage had been caused by water running across road embankments and pavements causing damage to both gravel and sealed pavements. Typically lengths of damaged road were between 50m and 100m.
Impacts on coastal roads	Many of Vanuatu's roads run parallel to the shoreline. Although not reported as the major cause of road damage due to climate change, some PWD staff noted that some coastal roads were experiencing local damage due to the impact of increased wave action during storms. It is unclear whether sea level rise is also playing a part in the increased level of damage being experienced by coastal roads. PWD reported that some sections of road in Malekula had been relocated inland because the original road near the sea was often damaged and inundated by sea water due to storm surges. In Tanna, ADB financing had been used to provide additional sandbag protection to sections of the new South Coast Road, but this has proved unsuccessful with many sandbags being washed away during storm surges.
Increased rainfall intensity causes major damage at watercourse crossings	By far the most common cause of recent climate event damage to the road network is caused at road/watercourse interfaces. At many locations, the volume and velocity of water crossing the road is reported to be higher than previously experienced in living memory, although precise volume/depth/velocity records at each location are generally unavailable.
Culverts and structures often incorrectly sized	Culverts designed for 1-in-50 year storms were being damaged during cyclones. Even roads around culverts situated in dry creeks were being washed out during cyclone-induced flows. PWD staff noted that usually damage was caused by culverts being of insufficient size to cope with volumes of water generated during cyclone events. This applies to all types of culvert: box, slab and armco. If culverts were of insufficient size to deal with flows, the damage could be significant with scouring around portals (wingwalls and approach slabs) and overtopping of road embankments with pavements being washed away. In some cases wingwalls and cut-off walls were insufficiently sized and were left exposed or undermined. The revised design guide should include clear guidance on how to calculate likely flows at culverts and how to convert this to an appropriate culvert size and type with appropriate protection. Worked examples would be useful. Many culverts are currently being sized as part of design without any hydrology study at all. There is a lack of historic design data available at each culvert location such as previous flood heights, flow volumes, depths of scour, etc. PWD engineers recommended that cut-off walls be deepened to increase resilience to undermining.

Storm debris causes blockages	Many major road failures have recently been caused by culverts or bridges becoming blocked due to storm debris being carried along a watercourse. Debris includes soils, gravels, trees and parts of trees. Once culverts or bridge openings become blocked, the water overtops the road causing significant scour of embankments and road pavement. Protective structures such as wingwalls and slabs are often undermined and become exposed. In Tanna, two of the culverts which became blocked by debris had 12m spans. This is important feedback because it demonstrates that sizing culverts and bridges to deal with water flows alone is insufficient to prevent overtopping and significant damage.
Heavy rainfall results in new drainage paths	PWD engineers reported that during very heavy rainfall, existing watercourses were often unable to contain flow volumes, and this resulted in new drainage paths being formed. In some areas water has been seen running alongside roads in locations where this has not been seen previously. Typically there are no drains installed alongside such roads so damage to pavements can be significant.
Damage occurs at the foot of steep gradients	In some cases, heavy rainfall causes water to flow along or alongside steep sections of road, especially where road pavements have been formed of concrete. This has resulted in significant damage to embankments and road pavements at the foot of the slope, especially if water flowed across the road at this point.
Concrete structures are generally resilient	PWD engineers reported that culverts, bridges, associated wingwalls, slabs and drifts[7] constructed in reinforced concrete were generally resilient to storm damage although scour of soils and pavement around such structures did occur. Evidence suggests that drifts generally provide a resilient solution to the design of watercourse/road interfaces. Some damage to concrete structures had occurred in Tanna.
Concrete pavements	Concrete pavements had generally performed well during recent cyclones. The most common form of concrete used now is fibre-reinforced concrete. There was a consensus that Vanuatu should construct more concrete pavement, but also realisation amongst interviewees that there is insufficient budget to create significant lengths of concrete pavement. R4D2 had recently created a 2.7km length of concrete pavement in Torba.
Gravel pavements	Gravel pavements, if subjected to significant water flows during storms, were not resistant to scour. Many gravel pavements had been damaged during recent cyclones. The performance of gravel pavements varied significantly from area to area. Recent efforts to introduce crushed gravel as a more resilient pavement had achieved mixed results. Small crushers had been trialled but could not produce the volumes of gravel required for practical road construction. On Malekula Island, a large stockpile of aggregates (20,000m^3) had been created as part of a major road project and is available for use on Malekula only. Typically, smaller contractors on other islands did not use crushers but there was some use of rock screens (grizzlies) to remove large particles before use. On remote islands there is very little processing of as-dug aggregates which are used directly to create gravel roads. Storm damage to gravel roads occurs more frequently on gravel roads which do not have side-drains or where side-drains had been filled or blocked.

[7] Drifts are concrete sections of strengthened road pavement which allow water to flow across the road surface at a watercourse/road interface. Many

Sealed pavements	The performance of sealed pavements under cyclone conditions was mixed. For example, sections of the South Tanna Road, which was constructed as DBST[8], did not perform well with many sections suffering from scour due to water action. There are similar examples of DBST failure on Malekula. The DBST pavements that had been damaged require a fresh seal. This is particularly difficult for PWD as they only have access to hand-held bitumen emulsion sprayers. Only a few large contractors have larger towed sprayers.
Pavement damage at culverts	It was suggested that extended lengths of concrete pavement at each culvert location could improve resilience significantly as washout of the road pavement would be avoided or at least reduced.
Wing walls and return walls at culverts	Often wingwalls are constructed at culverts without the added protection to the embankment provided by a return wall[9] in accordance with Standard Drawing SD18. Embankments would be better protected if return walls are constructed.
Effectiveness of gabions	There had been a number of instances of gabions being washed away by storms, mostly as a result of the gabion mesh being broken during heavy water and debris flows. It was suggested that the outer face of gabions could be mortared to avoid damage to the mesh basket. This technique had worked well in Papua New Guinea (PNG).
Bailey Bridge - Tanna	Many interviewees referred to the Bailey Bridge in Tanna that had recently been swept away by strong currents following cyclone storms. The mode of failure was that the gabion abutments which supported the Bailey truss were washed away. Interviewees confirmed that the bridge crossed a creek which was usually dry. The issue from a design perspective seems to be that the bridge truss was not set high enough to avoid the high flood water level. It is likely that no assessment of likely flood level had taken place during design.
Drifts versus culverts	It was generally acknowledged that drifts provided a more resilient solution than culverts for small watercourse crossings of roads. Although some scouring of embankments and pavement around drifts had occurred, the concrete drifts themselves had survived. Drifts are particularly useful for roads in low-lying areas. Extending concrete pavement to either side of a drift was suggested to further improve resilience.
Side drain effectiveness	Generally, where side drains were constructed parallel to the road, they had performed fairly well during cyclone events. However, some interviewees noted that there was evidence that some drains were under-sized and were unable to contain heavy flows during cyclones. There was more damage to road embankments and pavements along those sections of road without drains (or with small drains or with drains that were blocked).

[8] DBST (double bituminous surface treatment) is a common type of pavement surfacing construction which involves two applications of asphalt binder material and single-sized mineral aggregate. The asphalt binder material is applied by a pressure distributor, followed immediately by an application of mineral aggregate, and finished by rolling. The process is repeated for the second application of asphalt binder material and mineral aggregate. The first application of aggregate is coarser than the aggregate used in the second application and usually determines the pavement thickness. The maximum size of mineral aggregate used in the second application is about one-half that of the first. Strict control of aggregate sizes is required to produce a resilient pavement.

[9] A return wall is a wall parallel to the road which provides added protection to foot of the road embankment near to a culvert inlet or outlet.

2.3.3 *Other relevant findings and comments during PWD and R4D2 interviews:*

Other key findings were as follows:

Prioritisation of works	Some comments were received in relation to ongoing issues with prioritisation of works. For example, budgets were often spent on new sections of sealing, whist existing sealed sections were not being maintained due to lack of budget.
General construction quality	Some interviewees suggested that lack of resilience of Vanuatu's roads was caused by low quality construction rather than inadequate designs. It was suggested that many resilience issues could be resolved by following existing specifications. These compliance issues need to be addressed as well as updating design guidance if Vanuatu is to improve the resilience of its infrastructure.
Quality of sealing works	It was noted that the quality of some sealing works carried out by PWD's force account teams was sub-standard and therefore the pavement was not resilient to water damage, resulting in the early formation of potholes within 6 months of sealing.
Quality of aggregate materials	The quality of aggregates/gravels used for road sub-base, base and wearing course layers was often sub-standard. The key quality issues are aggregate grading outside acceptable grading curve limits and a lack of angular materials because as-dug gravels are being laid without any processing. There are examples of roads which were constructed of well-graded crushed gravels and with side drains in 2016 which are still in good condition. A serious commitment to improving the quality of road construction materials is required.
Construction of new roads	PWD were often instructed to construct new roads in a short space of time to meet political expectations. Many of these roads are constructed without prior surveys, design or appropriate preparation of contract documents including drawings and particular specifications. Many such contracts were awarded as a time-based contract rather than an agreed price because design details and quantities are unknown. Many of these roads become impassable within 6 months of opening due to their poor quality. It would therefore be useful if the revised design guide includes a section on the creation of new roads.
Cyclone Response Strategies and Plans	PWD has no specific standard operating procedures (SOPs) to be followed before, during or after a cyclone event in relation to road works. It was acknowledged that a cyclone readiness and response plan could be useful for Vanuatu, although little budget was available for cyclone preparatory works. PWD's current response to the cyclone season is reactive.

2.4 Key Consultation Findings - VAN-Kirap Team

2.4.1 Van-KIRAP Climate Information Services Portal

This portal, which is under development, holds important climate information for road designers. Based on the key consultation findings from PWD staff described in the previous section, obtaining predictions of future rainfall levels will be key to designing critical road/watercourse interfaces. Gaining an understanding of predicted rainfall intensity is key to determining likely flows during storms and cyclones at each road/watercourse interface. A guide to the portal is included in Annex D.

The portal provides rainfall and temperature forecasts which can be varied according to:

- monthly, seasonal or annual averages;
- future time periods: 2021-2040, 2041-2060, 2061-2080, 2081-2100;
- low (RCP2.6) or high (RCP8.5) greenhouse gas emissions pathways, and
- low or high climate change models[10]

The user can easily select and compare alternative future time periods, seasons, climate variables, emissions pathways, or climate projections with the results displayed in map form. Resulting climate maps can be downloaded. The portal also includes a query tool which allows users to identify forecast rainfall and temperature a specific point within Vanuatu.

2.4.2 Selecting Appropriate Climate Models and Emissions Pathways

The Van-KIRAP team looked into some of the more recent literature on greenhouse gas emission pathways and climate modelling and raised the following pointers as input to developing a road design methodology:

- the Paris Agreement target of keeping global warming below 2°C aligns with SSP1-2.6 (equivalent to RCP2.6 in the Van-KIRAP work, although not studied for extreme rainfall projections) which gives 1.3-2.4 °C global warming by 2081-2100;
- current climate policies would lead to 2.1-3.9°C of global warming (Liu and Raferty, 2021), aligned with SSP2-4.5 (equivalent to RCP4.5 in the Van-KIRAP work) which gives 2.1-3.5°C by 2081-2100 (IPCC, 2021). There is only a 5% probability of staying below 2°C (Liu and Raftery, 2021);
- current government pledges and targets (Nationally Determined Contributions) would lead to 2.2-3.4°C global warming, also aligned with SSP2-4.5 (equivalent to RCP4.5 in our Van-KIRAP work) which gives 2.1-3.5°C by 2081-2100 (IPCC, 2021), and
- if current climate policies and NDCs are not fully implemented (as is likely as demonstrated by recent history), then a stress test with higher global warming is relevant. SSP3-7.0 (not studied in the Van-KIRAP work) gives 2.8-4.6°C by 2081-2100,

[10] For temperature and rainfall, the low change projection is based on data from the IPSL-CM5A-LR model, and the high change projection is based on data from the GISS-E2-H model.

while SSP5-8.5 (equivalent to RCP8.5 in the Van-KIRAP work) gives 3.3-5.7°C by 2081-2100 (IPCC, 2021).

For road design, it is important to obtain a practical and pragmatic balance between the limited resources available for road construction and the need to make roads more resilient to climate change. Creating a fully resilient road network is unaffordable, especially in a resource-constrained country such as Vanuatu. During further discussion with the Van-KIRAP team it was broadly agreed that a two-tier approach to road design was required, using a 'no-regrets' policy for critical road infrastructure and a less onerous set of design rules for less critical infrastructure. This aligns well with the latest PWD Roads Strategy which defines a network of 'core roads' on each major island.

Broadly it was agreed that as a starting principle the RCP8.5 emissions pathway should be used to inform the design of critical infrastructure, whilst RCP4.5 could be adopted as the basis for the design of less critical infrastructure, noting that there is little difference in rainfall projections over 20 years between the two emissions scenarios. However, differences in rainfall predictions are noticeable over a 50-year period.

The updated road design guidance should be reviewed in 5 to 10 years' time based upon actual climate data and levels of resilience achieved. Further adjustments to the road design manual may be required in the future.

2.4.3 Rainfall Data and Projections

The Van-KIRAP team provided a preliminary analysis of the 99th percentile change in rainfall across Vanuatu based upon 7 different CIMP5 climate models for both the RCP4.5 and RCP8.5 emissions pathways. This data is presented in Annex E. The ranges of percentage change derived from the various models are plotted below for Port Vila (Efate), Port Resolution (Tanna) and Luganville (Efate). This suggests that Port Vila (Efate) forecasts provide us with the highest likely increase in rainfall, whilst Port Resolution (Tanna) provides us with the lowest likely change. Luganville (Santo) sits broadly in the middle of these two.

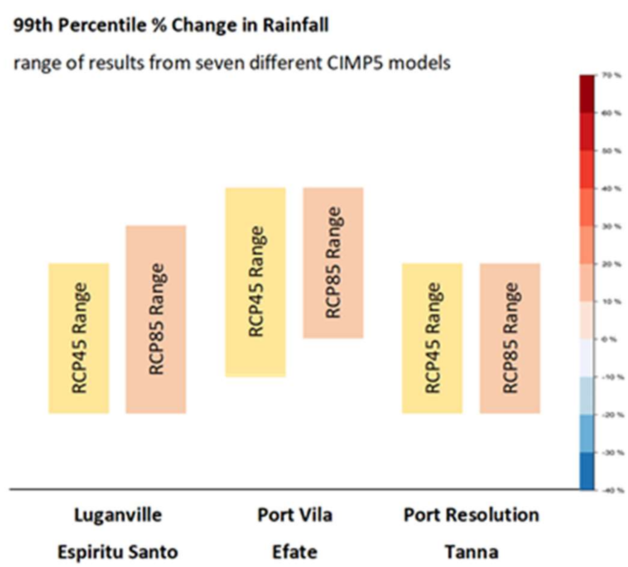


Figure 3: 99th Percentile % Change in Rainfall

Therefore, it was agreed that the Van-KIRAP team provide an extraction of yearly maximum rainfall data and percentage change in rainfall for both Port Vila (Efate) and Port Resolution (Tanna) representing the likely highest and lowest expected changes in rainfall.

This data was developed by the Van-KIRAP team. Annex F provides a technical report on the rainfall forecasts provided, and Annex G provides a summary of the derived forecasts.

In summary, for extreme daily rainfall with return periods of 10-100 years, the multi-model mean results for Port Vila showed an increase of about 21% for 2040-2070 (RCP4.5), 30% for 2070-2100 (RCP4.5), 40% for 2040-2070 (RCP8.5) and 70% for 2070-2100 (RCP8.5). For return periods of 10-100 years, the multi-model mean results for Port Resolution showed an increase of about 18% for 2040-2070 (RCP4.5), 27% for 2070-2100 (RCP4.5), 26% for 2040-2070 (RCP8.5) and 57% for 2070-2100 (RCP8.5). These forecast increases in rainfall have significant implications for future flood and watercourse flow predictions and will make a significant difference to the design of road/watercourse interfaces.

3. FINALISED SCOPE AND WORK PLAN

3.1 Adjusted Scope of Works

Based on the findings in Section 2, a revised and more detailed set of tasks to be undertaken for the project has been developed as described in Table 2 below.

Deliverable Stage	Detailed Tasks	Overview of Final Output
Deliverable 1a: Inception and stakeholder consultation report	• Develop Survey Questionnaire looking for good and bad practices • Analyse survey returns • Undertake initial interviews with PWD and R4D2 • Collect PWD/R4D2 evidence and photographs • Collect relevant PWD documentation • Undertake initial meetings with Van-KIRAP team • Collect rainfall forecast information for road design • Develop Report 1a	An inception and stakeholder consultation report detailing the required scope of the work to be undertaken under the Service Agreement; findings from the consultations, and details of who was consulted.
Deliverable 1b: Gap analysis, stocktake and benchmarking of climate resilient gaps in rural and urban roads.	• Literature Review – Vanuatu including operational reports such as TC Harold Assessment • Literature Review – International Design Codes • Identify and log gaps and issues relating to improved climate resilience • Identify and log gaps and issues relating to making the design guidance more user-friendly • Develop initial framework/structure for revised road design guide • Develop Report 1b	The gap analysis report is to clearly articulate findings from the literature review and benchmarking activity, including the identification of climate resilience gaps in rural and urban roads.
Deliverable 2: Draft Vanuatu Road Design Guidelines	• Update logs of gaps and issues with proposed solutions to be incorporated into new road design guide • Finalise and agree structure for new road design guide • Develop technical design guidance on sizing culverts/bridges at road/watercourse interfaces – discuss and agree with PWD/R4D2 • Develop graphics and select photographs for new road design guide • Develop full text for new road design guide	A draft of the updated Vanuatu Road Design Guidelines, including new content relating to climate resilient urban roads. Recommendations for PWD consideration on additional technical specifications and standard drawings. Presentation to the PWD and stakeholders on the draft Guidelines

Deliverable Stage	Detailed Tasks	Overview of Final Output
	• Recommend changes to standard drawings and specifications • Make online presentation to PWD, SPREP and stakeholders on draft road design guide • Issue draft new road design guide	
Deliverable 3: Final Vanuatu Road Design Guidelines	• Finalise and issue new road design guide based on feedback • Update and issue PWD standard drawings • Update and issue PWD standard specification	The final version of the Vanuatu Road Design Guide incorporating approved technical specifications and drawings.
Deliverable 4: Training of PWD personnel in the Vanuatu Road Design Guidelines Training and evaluation report (to be undertaken in Vanuatu)	• Prepare presentation and training workshop material • Hold orientation presentation in Vanuatu (philosophy/rationale, key objectives and key features of the new road design guide) for key decision-makers and leaders • Hold training presentations and workshops in Vanuatu including worked design examples • Undertake training evaluation and issue evaluation report including revised training material if appropriate based on feedback.	Undertake training of PWD personnel in the new Vanuatu Road Design Guidelines. Copies of all training materials are to be provided to PWD and SPREP. The training and evaluation report is to include the training objectives, training outline, course materials, list of participants and results from a training evaluation survey provided to participants at the end of the training session(s).

Table 2: Detailed Task List

3.2 Adjusted Task and Deliverables Schedule

Based on the above, and the delays caused by the double cyclone event described in Section 2.2, a revised task schedule was agreed with PWD and SPREP as shown in Figure 4 below.

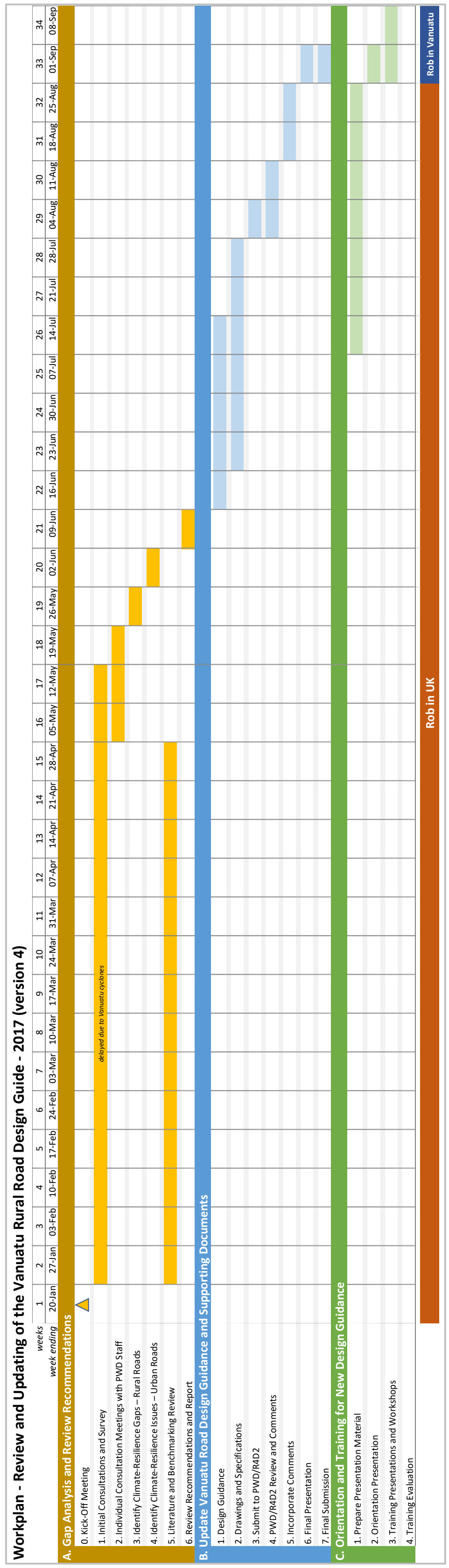


Figure 4: Revised Work Plan

The resulting deliverables schedule with anticipated delivery dates is as shown in Table 3 below:

Deliverable	Name	Delivery Date
1a	Inception and Stakeholder Consultation Report	9 June 2023
1b	Gap Analysis Report	16 June 2023
2	Draft Vanuatu Road Design Guide	4 August 2023
3	Final Vanuatu Road Design Guide	1 September 2023
4	Training Material and Training Evaluation Report	8 September 2023

Table 3: Final Deliverables Table

3.3 Training Mission to Vanuatu

A detailed agenda for the training mission to be held in Vanuatu between 28 August and 8 September has been agreed with PWD and SPREP. This is included as Annex H.

Annex A – Record of Kick-Off Meeting 18 January 2023

Attendees:

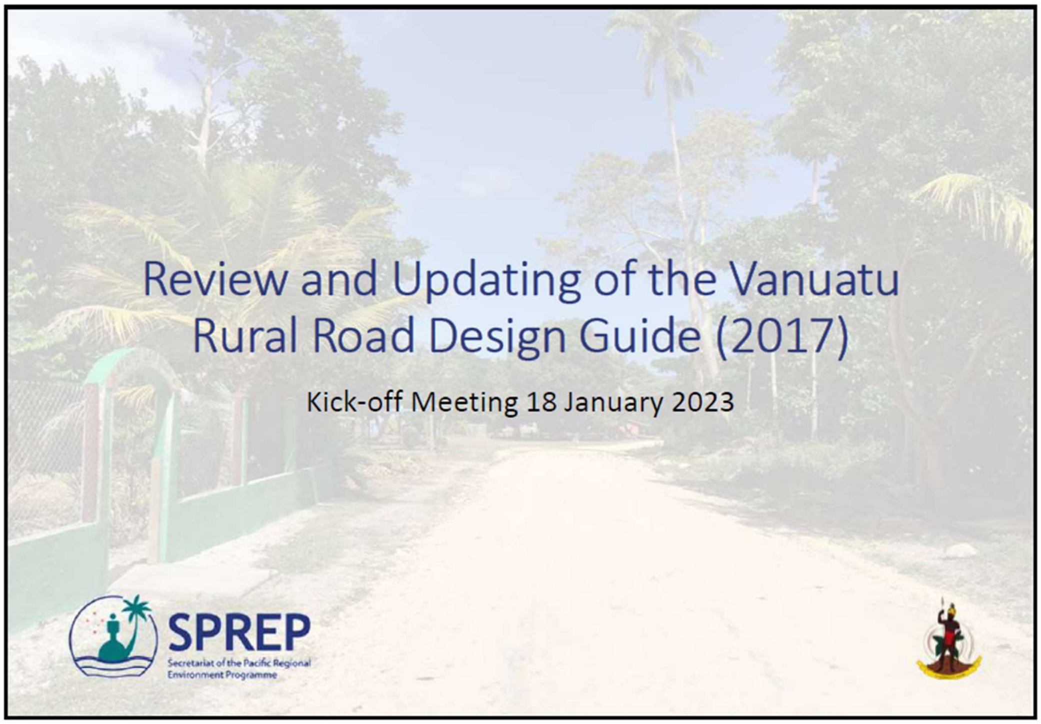
7Dee Consult	SPREP	PWD	R4D2
Robert Hardy	Moirah Matou	Raviky Talae	Eric Stensness
	Sunny Seuseu	Ambatha Paraliu	Ben Roberts
			Rajesh Sharma
			Chitra Thapa

Meeting Record

The key issues and actions arising from the meeting were as follows:

Item	Description	By
1.	PWD agreed to develop a project contact list to support stakeholder consultations.	Raviky Talae
2.	SPREP to open up a folder on their shared drive for sharing of project data and documents.	Sunny Seuseu
3.	It was noted that there were no restrictions on data sharing across the project.	All
4.	Robert Hardy presented kick-off slides for the project which are shown below.	

Meeting Presentation:



1

2

SPREP Regional Goals

- **Regional Goal 1:** Pacific people benefit from strengthened resilience to climate change;
- **Regional Goal 2:** Pacific people benefit from healthy and resilient island and ocean ecosystems;
- **Regional Goal 3:** Pacific people benefit from improved waste management and pollution control;
- **Regional Goal 4:** Pacific people and their environment benefit from commitment to and best practice of environmental governance.

SPREP

3

Extract from Project RFT

Vanuatu is among the most vulnerable countries on earth to the increasing impacts of climate change, including climate related natural disasters and the effects of slow-onset events such as the sea-level rise and ocean acidification

SPREP

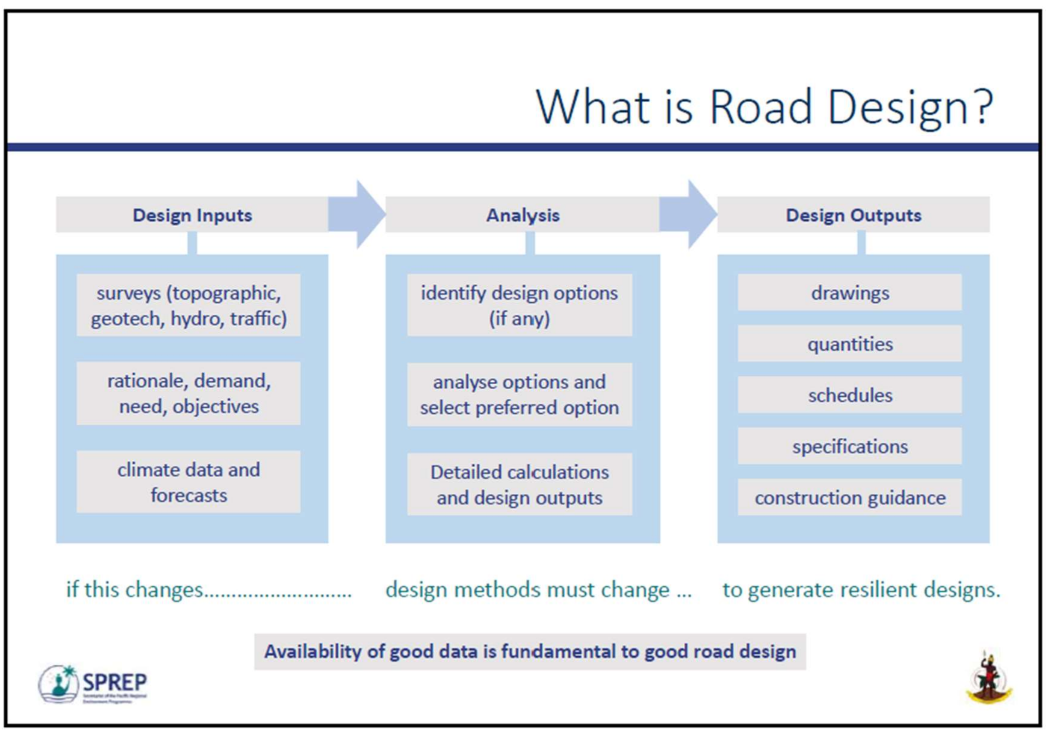
4

Vanuatu Road Sector Challenges

A reminder - it is important that we understand the difficulties and costs associated with our road network. We are faced with unique and difficult challenges in Vanuatu compared to many other countries:

Our geography	made up of many dispersed islands making the logistics of road construction and maintenance difficult, slow and costly
Our climate	heavy rains and cyclones during the rainy season cause significant damage to our roads every year
Our materials	the local coronous gravels available for road construction in Vanuatu are not ideal road-building materials compared to many countries
Our capacity	we are a small population with very few civil engineering graduates available to build up a competent professional road sector
Our funding gap	typical annual PWD roads budget is insufficient to maintain the existing 3,000km road network

5



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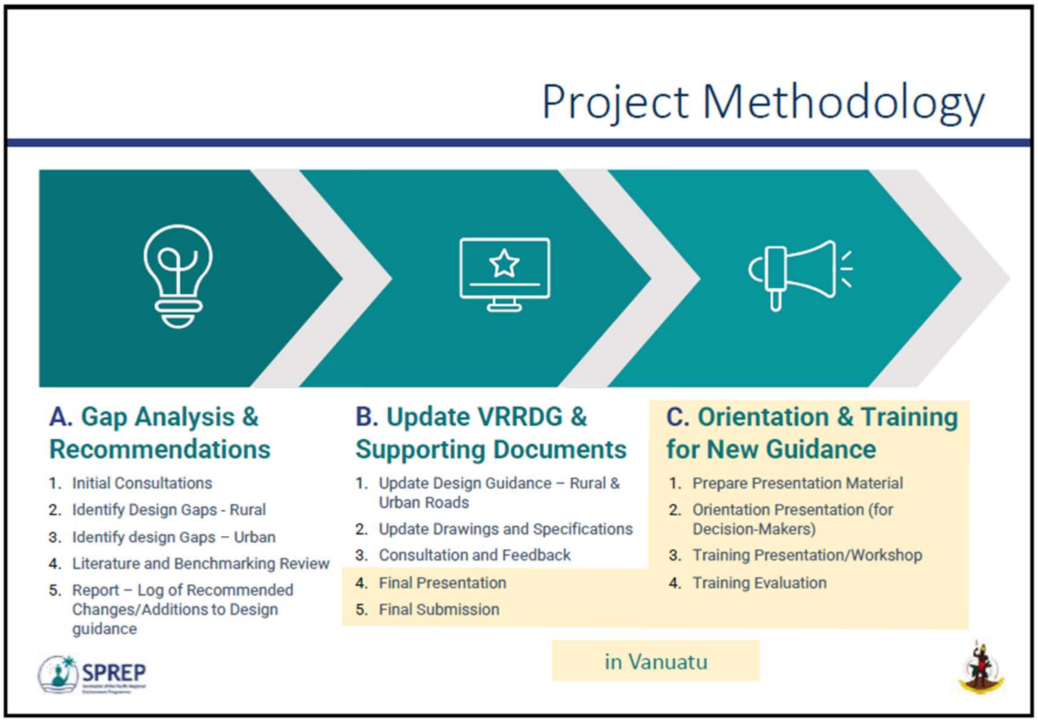
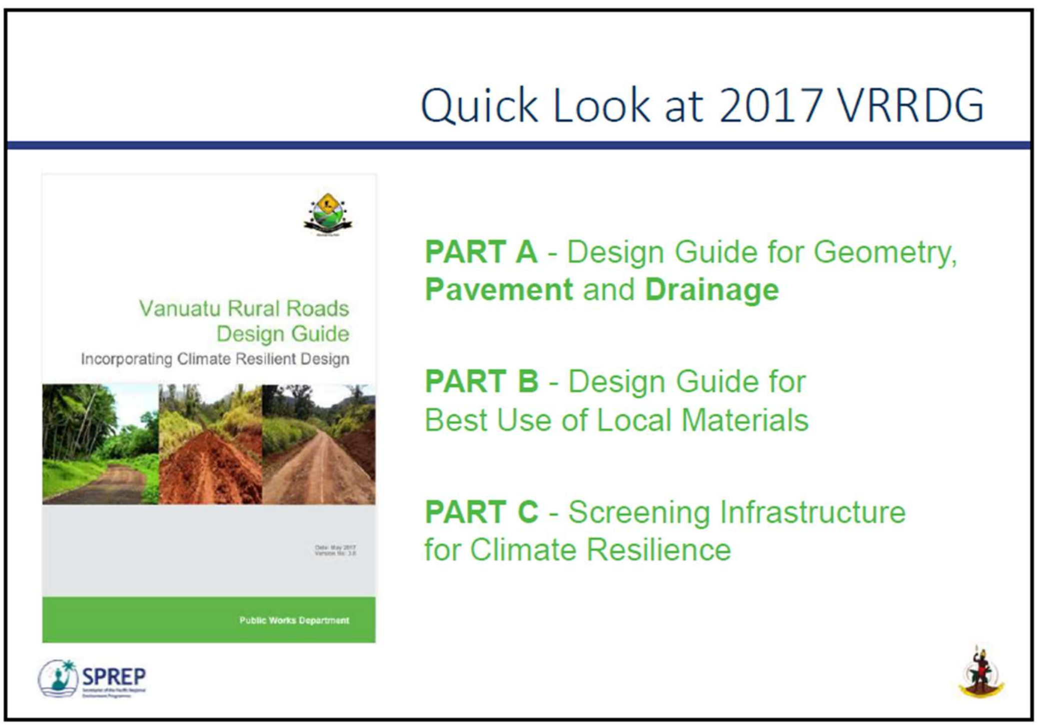
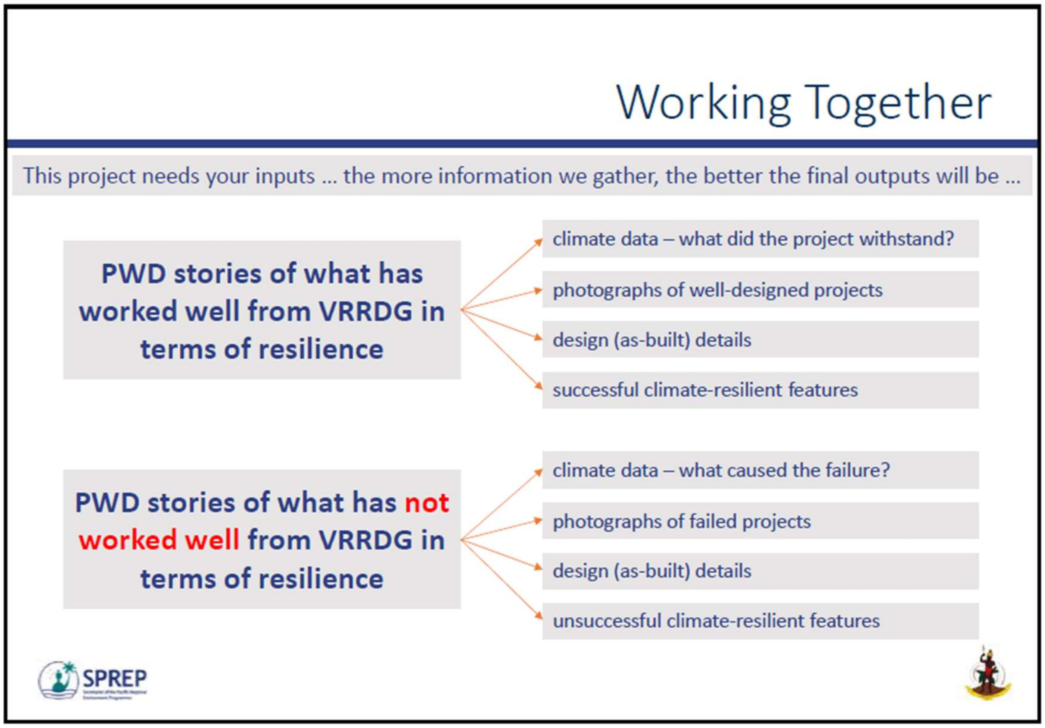

Project Methodology
A. Gap Analysis & Recommendations
1. Initial Consultations
2. Identify Design Gaps - Rural
3. Identify design Gaps – Urban
4. Literature and Benchmarking Review
5. Report – Log of Recommended Changes/Additions to Design guidance
B. Update VRRDG & Supporting Documents
1. Update Design Guidance – Rural & Urban Roads
2. Update Drawings and Specifications
3. Consultation and Feedback
4. Final Presentation
5. Final Submission
C. Orientation & Training for New Guidance
1. Prepare Presentation Material
2. Orientation Presentation (for Decision-Makers)
3. Training Presentation/Workshop
4. Training Evaluation
in Vanuatu
SPREP

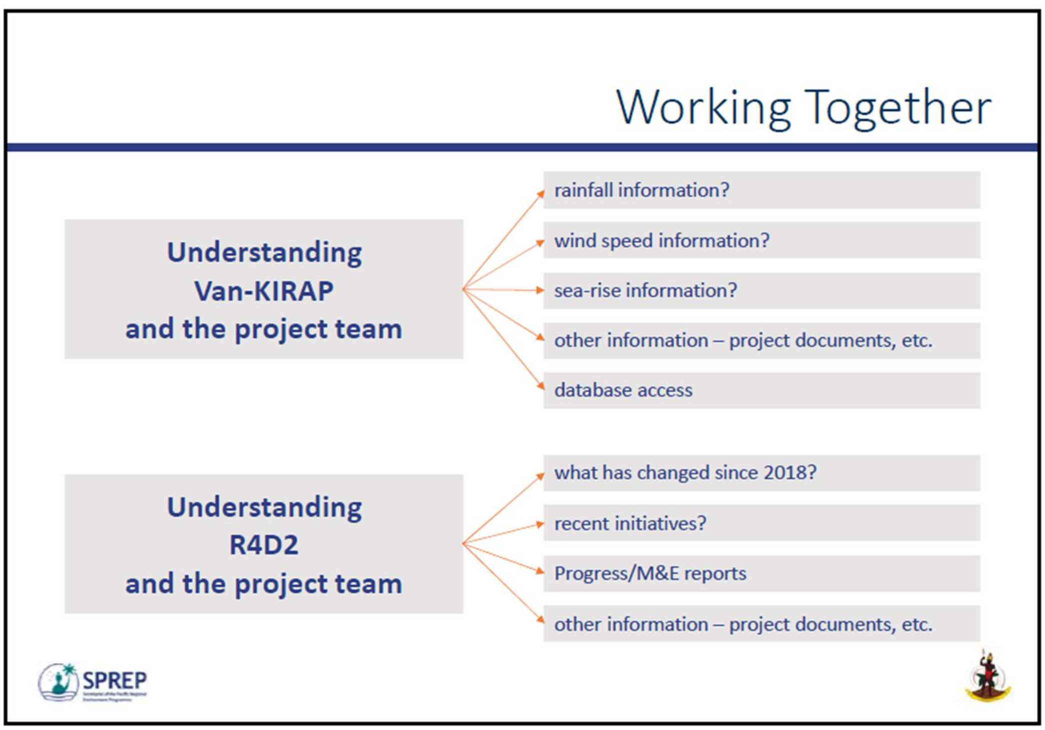
7


Quick Look at 2017 VRRDG
Vanuatu Rural Roads Design Guide
Incorporating Climate Resilient Design
Public Works Department
PART A - Design Guide for Geometry, Pavement and Drainage
PART B - Design Guide for Best Use of Local Materials
PART C - Screening Infrastructure for Climate Resilience
SPREP

8

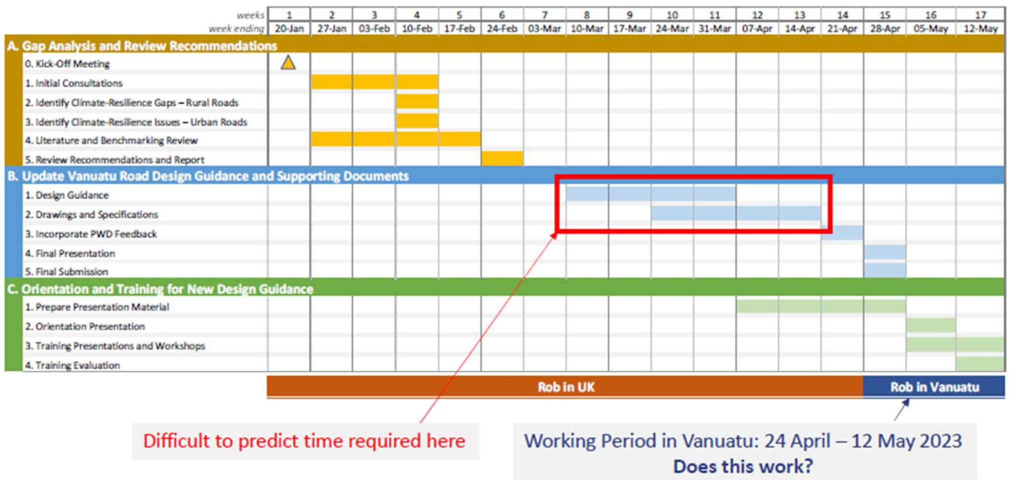

Working Together
This project needs your inputs … the more information we gather, the better the final outputs will be …
PWD stories of what has worked well from VRRDG in terms of resilience
climate data – what did the project withstand?
photographs of well-designed projects
design (as-built) details
successful climate-resilient features
PWD stories of what has not worked well from VRRDG in terms of resilience
climate data – what caused the failure?
photographs of failed projects
design (as-built) details
unsuccessful climate-resilient features
SPREP

9


Working Together
Understanding Van-KIRAP and the project team
rainfall information?
wind speed information?
sea-rise information?
other information – project documents, etc.
database access
Understanding R4D2 and the project team
what has changed since 2018?
recent initiatives?
Progress/M&E reports
other information – project documents, etc.
SPREP

10

Project Schedule



11

Immediate Tasks

	Actions	by
1	Produce Project Key Contact List – Names, Roles, Organisation, Email, Phone.	?
2	Set up Portal for Shared Information, Set up Whatsapp Group?	In Vanuatu or Rob?
3	Develop Questions for Meetings and Survey Questionnaires	Rob
4	Schedule and Hold PWD Meetings, Issue Survey Questionnaires	Rob
5	Schedule and Hold Van-KIRAP Meeting	Rob
6	Share Latest Project Information	R4D2, Van-KIRAP
7	Share Original Electronic Versions of VRRDG, Specification, CAD Drawings	PWD
8	Confirm RPH Dates for Trip to Vanuatu are OK	All

12


Thank you for listening
Kick-off Meeting 18 January 2023
SPREP
Secretariat of the Pacific Regional
Environment Programme

13

Annex B – Survey Questionnaire

Review and Updating of the Vanuatu Rural Road Design Guide (2017)

SPREP
Secretariat of the Pacific Regional Environment Programme

Survey Questionnaire

Introduction

This main objective of this questionnaire is to develop an improved understanding of how Vanuatu's roads have performed during adverse weather conditions. The survey also solicits feedback on the current version of the Vanuatu Rural Road Design Manual (2017). The results from this survey will be used to identify areas where design guidance contained in the Vanuatu Rural Road Design Guide needs to be strengthened, adjusted or supplemented to deal with the impacts of increasingly severe weather conditions due to climate change.

Respondents should try to identify and provide information in relation to key examples of road sections which have experienced severe weather impacts over the last 3 to 5 years. Examples to be provided by respondents will fall into three broad categories:

- sections of road which were able to withstand adverse weather conditions without damage;
- sections of road which showed signs of failure under adverse weather conditions, but which required only minor repairs and which remained open to vehicles, and
- sections of road which suffered significant damage during adverse weather events causing road closure and requiring extensive repair or reconstruction.

Learning from road sections which perform well during weather events is just as important as learning from examples where roads have failed.

Respondents should include examples of both rural and urban roads if these are available. Respondents should try to provide as much back-up evidence as possible including, where available, precise locations of damage to roads, descriptions and photographs of roads before and after weather events, dates when the damage occurred and the original road design details. Additional files may be submitted with the returned questionnaire.

This questionnaire has been distributed to staff in both PWD and the DFAT-supported R4D2 team as shown in the list below.

PWD

Ambatha Paraliu - Operations Manager
Nathan Tabi – Principal Engineer
Fred Siba – Principal Engineer Projects
Harold Allanson – Project Engineer
Morgan Ngwango – Project Engineer
Fredison Hosea – Divisional Manager (Malampa)
Danny Viroliliu – Divisional Manager (Penama)
Ronald Matavussi – Divisional Manager (Torba)
Jimmy Johnson – Divisional Manager (Shefa)

R4D2

Ben Roberts – Senior Engineering Advisor
Rajesh Sharma – Engineering Advisor – Planning
Chitra Thapa – Regional Operations Engineer
Patrick Mannix – Engineering Advisor – Projects

1

Review and Updating of the Vanuatu Rural Road Design Guide (2017)

Each respondent should complete Section A of the questionnaire. Section B of the questionnaire should be repeated for each weather event example provided. Respondents should provide survey responses as a completed word document, but with supporting documents attached and clearly identified.

2

SECTION A: FEEDBACK ON VANUATU RURAL ROAD DESIGN GUIDE (2017) & OTHER STANDARD DOCUMENTS

To be completed by each respondent who has used the VRRDG and other PWD design documents:

replace grey text in these boxes ↓

Survey Form Completed by:	[add full name]

VRRDG Feedback

In your experience, in general terms do you find the VRRDG to be too complicated for its intended use, or do you find it simple to use?	[add comments]
In your experience, do you find the overall structure and order of chapters in the VRRDG easy to follow? Do you have any suggestions to improve this?	[add comments]
In your experience, which sections of the VRRDG are easy to understand and implement during design? Please describe.	[add comments]
In your experience, which sections of the VRRDG are difficult to understand and are not very useful for road design in Vanuatu? Please describe.	[add comments]

PWD Standard Drawings

In your experience, in general terms, are PWD's standard design drawings easy to use during construction. Do contractors or in-house teams have difficulty understanding them? Please describe.	[add comments]
In your experience, which specific standard drawings are easy to understand and use during construction? Please describe	[add comments]
In your experience, which specific standard drawings are difficult to understand and use during construction? Please describe.	[add comments]

PWD Standard Specification

In your experience, in general terms, is PWD's Standard Specification a useful document and used during design and construction. Do contractors or in-house teams have difficulty understanding or following detailed specifications? Please describe.	[add comments]
In your experience, which specific sections of the Specification are easy to understand and use during construction? Please describe.	[add comments]
In your experience, which specific sections of the Specification are difficult to understand and use during construction? Please describe.	[add comments]

SECTION B: WEATHER EVENT EXAMPLES

To be completed by each respondent for each weather event example. Please complete as many boxes as possible, and attach supplementary information such as photographs, original drawings, etc. Please repeat Section B if providing feedback on multiple weather events (i.e. one Section B per weather event example:

replace grey text in these boxes ↓

Date(s) of Weather Event:	[add date or date range]
Location of Road Section:	[add a google map link or other marked up map of the event location]

Description of Weather Event:	[provide a description of the weather/climate event including the duration and any available data such as rainfall intensity, wind speeds, temporary sea rise, estimated or reported height of waves, name of cyclone if applicable, etc.]
Select the Most Appropriate Description of the Weather Event and Road Impact: **[select one only]**	☐ Road which was subject to adverse weather conditions but did not suffer damage
	☐ Road which was subject to weather-related damage but remained open and required minor repairs only
	☐ Road which was closed due to major weather-related damage and required significant repair before re-opening

Description of Road Section Prior to Weather Event (attach photographs when available):

Pavement surface type:	[e.g. Coronous Gravel, Volcanic Scoria, Loose Beach/Stream Gravel, Basalt Gravel (usually only on Ambae), Concrete, Thin Bituminous Seal Treatment (DBST, Otta Seal, etc.), Asphaltic Wearing Course, Cobble Pavement, etc.]
Thickness of upper pavement layer:	[in mm]
Further description of upper pavement layer:	[e.g. was the gravel 'as-dug' or crushed, was it considered stable (well-graded, well-compacted and generally free of potholes), etc.]
Pavement sub-base type (if any):	[e.g. Coronous Gravel, Volcanic Scoria, Loose Beach/Stream Gravel, Basalt Gravel (usually only on Ambae), etc.]
Pavement sub-base thickness:	[in mm]
Subgrade Strength:	[Subgrade description and strength if known from records (such as CBR)]
Description of Drainage Features:	[e.g. longitudinal drains (piped/open/lined/unlined/size), cross-drains (pipes/culverts/ bridges/drifts, size, construction materials), etc.]
Description of Retaining Features:	[e.g. description of retaining walls, gabions, heights, etc.]
Description of Road Topography and Context:	[gradient of road, horizontal alignment (straight/bend), road width, road crossfall, proximity of sea or river crossing, size of river crossing, etc.]
Age of Road	[if known, date when was this section of road was constructed or last re-constructed/resurfaced]

Original Road Design Details:	[if design drawings from the original construction/maintenance contract are available, please list here and attach]

Description of Mode of Failure and Damage Caused to Road Section

What was the principal mode of road failure?	[e.g. the road was damaged by wave action causing shoreline erosion, strong water currents crossing the road, drains undersized with road overtopping, strong water currents along the road, landslip undermining the road, landslip onto the road, general flooding of the area, etc.] - please attach photographs
Description of the damage caused to road elements:	[e.g. embankment washed away, pavement washed away, gabions washed away, drainage destroyed, etc.] – please attach photographs
Opinions on Reasons for Failure	[Describe whether you believe the road failure was due to substandard design (and state why), or substandard construction (and state why). For instance, do you think the road pavement would have remained in place if the gravel pavement had been well-graded and well-compacted, rather than a gap-graded gravel? Do you think the road would have been unaffected or less affected if design and construction guidance had been strictly adhered to?]

Preparation for Weather Event

Did the relevant PWD Division make any preparation for the adverse weather event - e.g. using sandbags for protection or flood control, cleaning out drains prior to cyclones/storms, etc. If so, please describe:	[Describe any preparation/protection for the weather event]
Was the preparation/protection successful (if applicable)?	[Describe whether you think the preparation/protection eliminated or reduced road damage]
If no preparation/protection was in place, do you think preparation/temporary protection would have eliminated or reduced road damage?	[Please give an opinion and reasons why – for instance, a blocked drain which could have been cleared caused overtopping of the road and resulted in erosion damage].

Repeat Section B to report on multiple weather events.

Annex C – Record of Recent Category 5 Tropical Cyclones in Vanuatu

Name	Duration	Peak Intensity		Areas affected	Damage (USD)	Deaths
		Wind Speed	Pressure			
Hina	March 10 - 19, 1985	220 km/h (140 mph)	910 hPa (26.87 inHg)	Solomon Islands, Vanuatu, Fiji	>$3 million	1
Fran	March 4 - 11, 1992	205 km/h (125 mph)	920 hPa (27.17 inHg)	Wallis and Futuna, Fiji, Vanuatu New Caledonia, Queensland, New Zealand	Unknown	Unknown
Susan	December 20, 1997 – January 10, 1998	230 km/h (145 mph)	900 hPa (26.58 inHg)	Solomon Islands, Vanuatu, Fiji	$100,000	1
Zoe	December 23 2002 - January 4, 2003	240 km/h (150 mph)	890 hPa (26.28 inHg)	Solomon Islands, Vanuatu, Fiji	Severe	None
Beni	January 19 - February 1, 2003	205 km/h (125 mph)	920 hPa (27.17 inHg)	Solomon Islands, Vanuatu New Caledonia, Australia	$1 million	1
Erica	March 12 - 14, 2003	215 km/h (130 mph)	915 hPa (27.02 inHg)	Queensland, Solomon Islands Vanuatu, New Caledonia	$15 million	2
Ului	March 14, 2010	215 km/h (130 mph)	915 hPa (27.02 inHg)	Solomon Islands, Vanuatu	Unknown	1
Pam	March 12 - 14, 2015	250 km/h (155 mph)	896 hPa (26.46 inHg)	Fiji, Kiribati, Solomon Islands, Tuvalu Vanuatu, New Caledonia, New Zealand	$360 million	16
Winston	February 18 - 21, 2016	280 km/h (175 mph)	884 hPa (26.10 inHg)	Vanuatu, Fiji, Tonga, Niue	$1.4 billion	44
Gita	February 13 - 14, 2018	205 km/h (125 mph)	927 hPa (27.37 inHg)	Solomon Islands, Vanuatu, Fiji, Niue Wallis and Futuna, Samoan Islands, Tonga	$221 million	2

Name	Duration	Peak Intensity		Areas affected	Damage (USD)	Deaths
		Wind Speed	Pressure			
Harold	April 2 - 9, 2020	230 km/h (145 mph)	920 hPa (27.17 inHg)	Solomon Islands, Vanuatu, Fiji, Tonga	Significant	29
Niran	February 25 – March 8, 2021	205 km/h (125 mph)	931 hPa (27.49 inHg)	Queensland, New Caledonia	Extensive	
Kevin	February 27, 2023 – March 6, 2023	215 km/h (130 mph)	925 hPa (27.32 inHg)	Solomon Islands, Vanuatu, New Caledonia	Unknown	Unknown

Annex D – Van-KIRAP Portal Guidance

Van KIRAP portal

Climate maps

Maps of past and future average *climate* can be viewed using this tool.

- Past climate (See map legend):
    - For average temperature and rainfall, 1970-2000 represents the past climate.
    - For Sea Surface Temperature (SST) and Marine Heat Waves (MHW), 1995-2014 represents the past climate.
    - For pH and ocean acidification (OA), 1986-2005 represents the past climate.
    - For Sea Level Rise (SLR), 1986-2005 represents the past climate.
    - For extreme sea levels, 1980-2020 represents the past climate.
- Future climate (See map legend):
    - Various future time periods can be selected: 2021-2040, 2041-2060, 2061-2080, 2081-2100.

You can also choose monthly, seasonal or annual averages.

You can select from a range of *climate variables*: mean temperature, maximum temperature, minimum temperature, rainfall, sea surface temperature (SST), sea level rise (SLR) and ocean acidification.

You can also choose a low (RCP2.6) or high (RCP8.5) ***greenhouse gas emissions pathway***.

You can choose from a selection of ***global climate models (GCMs)***:

- For temperature and rainfall, the low change projection is based on data from the IPSL-CM5A-LR model, and the high change projection is based on data from the GISS-E2-H model.
- For SST and marine heat waves 18 *CMIP6* models were analysed, for ocean acidification, a set of 6 *CMIP5* models were analysed - the low projection is the 10^{th} percentile (represents the lowest 10 percent of the model range), the medium projection is the 50^{th} percentile (middle value), and the high projection is the 90^{th} percentile (represents the highest 10 percent of the model range).
- For Sea Level Rise (XX models) - the low projection is the 5^{th} percentile (represents the lowest 5 percent of the model range), the medium projection is the 50^{th} percentile (middle value), and the high projection is the 95^{th} percentile (represents the highest 5 percent of the model range).

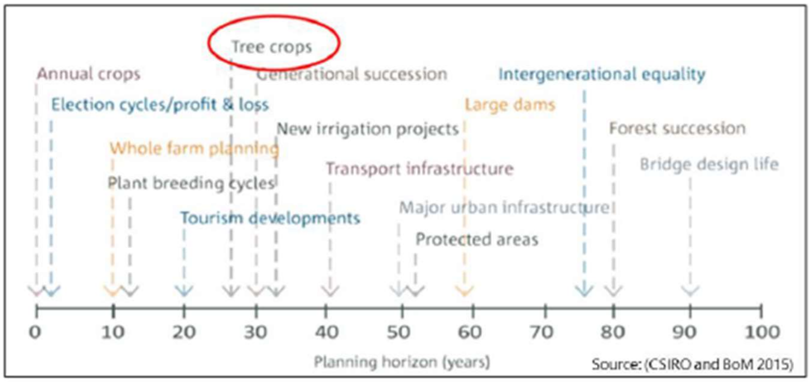
Once the map has been displayed, you can easily select and compare alternative future time periods, seasons, climate variables, emissions pathways, or climate projections. Maps can be downloaded as jpg files for use in communication products.

This information can be used to raise awareness about climate change and to guide adaptation plans.

Time period

You can select a past or future time period. Past climate data are generally averaged over 1986-2005, except for SST and ocean acidification which are averaged over XXXX-XXXX. The future time periods are 2021-2040, 2041-2060, 2061-2080, 2081-2100.

For impact assessment, select a period that aligns with the planning horizon of the infrastructure/asset/resource of interest. Typical planning horizons are shown below.



Season

Different averaging periods (annual, seasonal, monthly) may be relevant. For example, farmers and agricultural experts may want to assess how monthly-average temperatures or seasonal-average rainfall may change. Engineers designing bridges, roads or dams may want to assess annual-average climate information.

The annual-average is calculated from Jan-Dec. The season is averaged from May-Oct or Nov-Apr. Individual months can be selected.

Climate variable

You can select different climate variables: mean temperature, maximum temperature, minimum temperature, rainfall, sea surface temperature, sea level rise and ocean acidification.

Greenhouse gas emissions pathway

Climate scenarios provide internally consistent and plausible descriptions of the future, based on a range of assumptions about demographic change, socio-economic development, energy-use and land-use. These assumptions influence greenhouse gas emissions and concentrations. *Representative Concentration Pathways (RCPs)* and *Shared Socio-economic Pathways (SSPs)* have been used by the IPCC, researchers and decision-makers to explore the different climate scenarios.

For the VanKIRAP project, the high and low pathways are considered for most assessments, with the medium pathway used for some of the variables shown on the portal:

- Low – the world is following a pathway to decarbonise the economy with significant reductions in emissions (RCP2.6 or SSP1-2.6). The increase in greenhouse gas emissions is halted within around 20 years, leading to net zero emissions by 2070. According to the IPCC, this gives 1.3-2.4°C global warming by 2081-2100 (Figure 1).
- Medium - the world is following a path that implements current global emission reduction policies (RCP4.5 or SSP2-4.5). Greenhouse gas emissions continue to rise until 2050, then start to fall. According to the IPCC, this gives 2.1-3.5°C global warming by 2081-2100 (Figure 1).
- High – the world is following a pathway where limited emission reductions are implemented (RCP8.5 or SSP5-8.5). Greenhouse gas emissions continue to rise. According to the IPCC, this gives 3.3-5.7°C global warming by 2081-2100 (Figure 1).

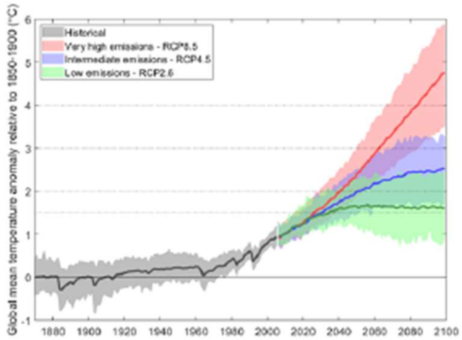


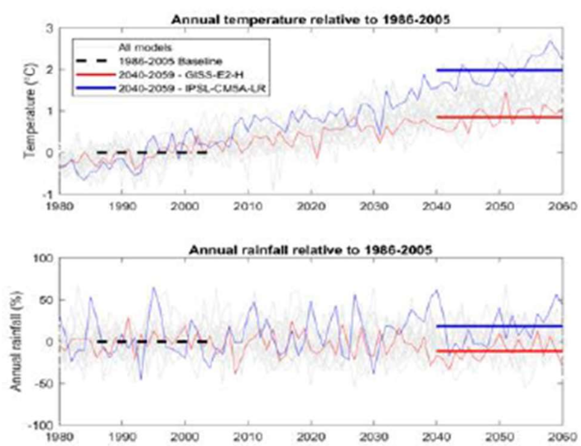
Figure 1: Global temperature anomalies relative to 1850-1900 for three Representative Concentration Pathways (RCP 2.6, RCP4.5 and RCP8.5). Shading indicates the range of uncertainty simulated by up to 40 climate models.

Projected climate change

Climate scenarios provide internally consistent and plausible descriptions of the future. They are based on data produced by 40-50 *global climate models*. These models can simulate global and regional climate projections in response to various future *greenhouse gas emissions pathways*. Different climate models produce different climate projections. For example, different climate models indicate that the *South Pacific Convergence Zone* could move either north or south, leading to a drier or wetter climate over Vanuatu. This also has an impact on other factors such as the amount of warming, sea level rise and cyclone activity. For planning purposes, a range of projections should be considered.

For temperature and rainfall, we recommend considering projections from models representing:

- Low projected change: A warmer and drier future (GISS-E2_R climate model)
- High projected change: A hotter and wetter future (IPSL-CM5A-MR climate model)



Modeled annual temperature (°C) and rainfall (%) changes in the Vanuatu region relative to 1986-2005 from 40 CMIP5 climate models, highlighting the two models that are representative of a warmer and drier future (GISS-E2-H, red) and a hotter and wetter future (IPSL-CM5A-LR, blue) for a high emissions pathway (RCP8.5).

When considering future ocean related variables: sea surface temperature, pH and ocean acidification, projections are also based on data from a range of climate models. We recommend considering a low projection (10th percentile or lowest 10 percent), a medium projection (50th percentile or middle value), and a high projection (90th percentile or highest 10 percent).

Similarly for sea level rise, the low projection is the 5th percentile (represents the lowest 5 percent of the model range), the multi model median is the 50th percentile (middle value), and the high projection is the 95th percentile (represents the highest 5 percent of the model range).

Climate graphs

A work in progress…

Graphs can be produced using this tool.

Graphs will show time series from 1980-2100 for selected climate variables, greenhouse gas emissions pathways, projected climate changes, regions and seasons.

Intensity versus frequency/probability graphs will highlight changes in extreme daily rainfall and windspeed.

Graphs can be downloaded as jpg files for use in communication products.

Area Council summary tables

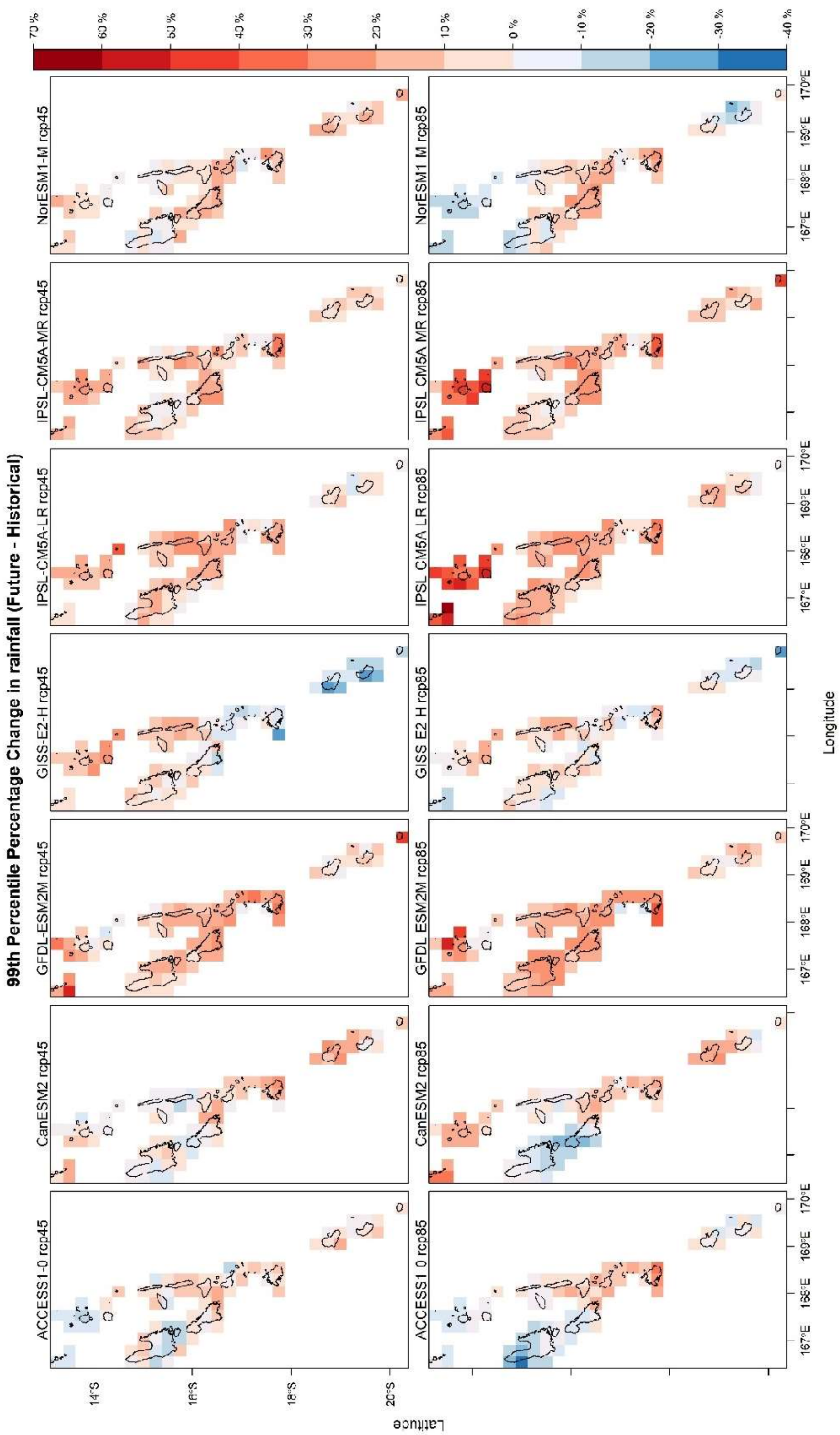
A work in progress…

Tables summarizing key results can be produced using this tool.

Tables will show average changes for selected time periods, climate variables, greenhouse gas emissions pathways, projected climate changes, regions and seasons.

Data can be downloaded in CSV or Excel files.

Annex E – Preliminary Analysis on the 99th Percentile Rainfall across Vanuatu



Annex F – Technical Report: Van KIRAP Rainfall and Windspeed Projections

By Savin Chand, Soubhik Biswas and Krishneel Sharma
Centre for New Energy and Transition Research, Federation University, Mt Helen Campus, Victoria, Australia

Kevin Hennessy, Leanne Webb and Geoff Gooley
CSIRO Environment, Aspendale, Victoria, Australia

Summary

This report provides a brief overview of the dataset and methodology used to create projection information for extreme rainfall and windspeed, as well as tropical cyclone intensity, for various locations in Vanuatu. Results for only two locations (Port Vila and Luganville) are shown as examples. Two time periods are considered (2040-2070 and 2070-2100), relative to a baseline of 1970-2000, for low (Representative Concentration Pathways, RCP4.5) and high (RCP8.5) greenhouse gas emissions scenarios, from 7-8 climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5, reader is referred to (van Vuuren et al., 2011) for details on RCP experimental designs).

For extreme daily rainfall with return periods of 10-100 years, the multi-model mean results for Port Vila showed an increase of about 21% for 2040-2070 RCP4.5, 30% for 2070-2100 RCP4.5, 40% for 2040-2070 RCP8.5 and 70% for 2070-2100 RCP8.5. For return periods of 10-100 years, the multi-model mean results for Luganville showed an increase of about 18% for 2040-2070 RCP4.5, 27% for 2070-2100 RCP4.5, 26% for 2040-2070 RCP8.5 and 57% for 2070-2100 RCP8.5. These increases have significant implications for future flood risk management strategies.

For extreme daily windspeed with return periods of 10-100 years, the multi-model mean results showed an increase in intensity of about 6% for Port Vila and 3% for Luganville by 2070-2100 for RCP8.5. These increases have implications for future cyclone risk management strategies.

Introduction

Vanuatu is highly exposed to climate variability and change. The Green Climate Fund is supporting the Van KIRAP Project which is delivering climate information services (CIS) to inform decision-making by sectors and communities in Vanuatu. This project is led by SPREP

(Secretariat of the Pacific Regional Environmental Program) in partnership with VMGD (Vanuatu Meteorology & Geo-hazards Department) and delivery partners including Australia's CSIRO (Commonwealth Scientific and Industrial Research Organisation) and Federation University, along with the APEC (Asia-Pacific Economic Co-operation) Climate Centre.

More specifically, Van KIRAP will develop and demonstrate application of CIS in five priority sectors: infrastructure, water, agriculture, fisheries and tourism. Sectoral case studies will include hazard-based climate change impact assessments for each of the sectors to facilitate development and demonstration of the application of CIS at multi-decadal timescales.

Van KIRAP will build the technical capacity of key sectoral stakeholders to use CIS including climate data, information, tools and other science-based resources. The project will support enhanced coordination and dissemination of CIS products and services to inform climate change impact/risk assessments and associated adaptation planning at sectoral level.

The water and infrastructure sectors require information about current and future extreme rainfall and wind. This technical report describes data and methods used to estimate extreme rainfall and windspeed intensity and frequency for Vanuatu. It is anticipated that the approach described in this report can be adopted for other countries in the Pacific, and elsewhere around the globe.

1. Rainfall and windspeed data and calibrations

Daily rainfall data

For the current and future projections of daily rainfall, this report uses station data, ERA5 reanalysis data and rainfall data from Coupled Climate Model Intercomparison Project phase 5 (CMIP5) climate models (Taylor et al., 2012).

Historical emissions, medium future emissions (RCP 4.5) and high future emissions (RCP 8.5) scenarios (Moss et al., 2010) were used for the seven CMIP5 models in the study (Table 1). These models were selected because (a) they perform well in simulating the current climate and (b) they represent a broad range of future climates.

Table 1. List of CMIP5 Models used for rainfall

CMIP5 Models	Historical period	RCP8.5 period	RCP4.5 period
ACCESS1.0	1850-2005	2006-2100	2006-2100
CanESM2	1850-2005	2006-2100	2006-2100
GFDL-ESM2M	1850-2005	2006-2100	2006-2100
GISS-E2-H	1850-2005	2006-2100	2006-2100
IPSL-CM5A-LR	1850-2005	2006-2100	2006-2300
IPSL-CM5A-MR	1850-2005	2006-2100	2006-2100
NorESM1-M	1850-2005	2006-2100	2006-2300

Since the above CMIP5 models had coarse spatial resolution (about 200 km between data points) and contain systematic biases, the output data need to be calibrated. This can be done using geospatial interpolation (Li and Heap, 2014) and bias correction (Piani et al., 2010). The following three steps were carried out to calibrate the above-mentioned CMIP5 models.

1. Fill in missing values in weather station data
2. Calibrate ERA5 reanalysis data on a 30 km grid using weather station data
3. Interpolate and bias-correct the climate model data using the calibrated ERA5 data

Step 1

Temporal homogeneity was ensured for daily rainfall data obtained from seven VMGD weather stations (see Table 2 and Figure 1) across Vanuatu by filling in missing values using the Inverse distance weighting (IDW) interpolation technique. IDW was chosen for its simplicity and low computation load (Li and Heap, 2014).

Table 2. List of VMGD weather stations

Station Name	Latitude (°E)	Longitude (°S)
Sola	167.55	13.85
Pekoa	167.22	15.52
Lamap	167.8	16.42
Bauerfield	168.3	17.7
Port Vila	168.32	17.74
White Grass	169.22	19.45
Aneityum	169.77	20.23

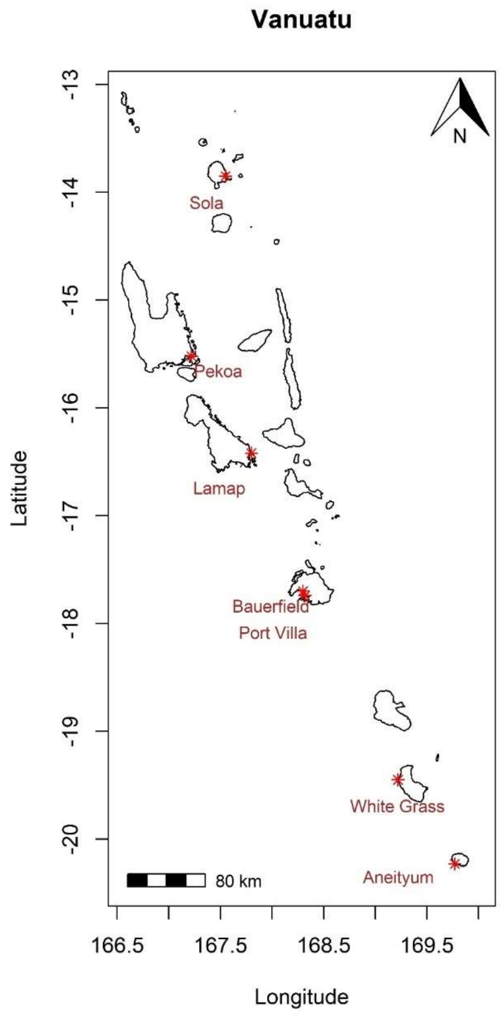


Figure 1. Map of Vanuatu showing the locations of VMGD weather stations.

Step 2

The ERA5 reanalysis dataset is available on a 30 km grid from 1940-2022. The daily accumulated rainfall for ERA5 is calculated from hourly ERA5 rainfall after accounting for the local time zone conversion from the UTC. The ERA5 daily accumulated rainfall data were then calibrated with the VMGD weather station data nearest to each grid point. This was done using quantile-quantile matching (bin size of 450) with the help of a cubic spline approach; this approach does not assume linearity and is more appropriate for calibration of extremes (Biswas et al., 2022). Note here that the 1961 – 2005 data were used as the training period to calibrate the ERA5 daily accumulated rainfall from weather station daily rainfall data (Table 3).

Table 3. ERA5 and station data for rainfall

Data	Station Data	ERA5	Calibrated ERA5
Spatial Resolution	NA	0.25° X 0.25°	0.25° X 0.25°
Temporal Resolution	Daily	Hourly	Daily
Time period	1961 – Present	1960 – Present	1961 – 2005

Step 3

The CMIP5 model data were then bilinearly interpolated to the spatial resolution of calibrated ERA5 data. The bilinear interpolation technique was selected, after comparing several other methods, due to its simplicity and being computationally inexpensive (Petrou and Petrou, 2010; Wolf et al., 2014). Though other approaches might offer better accuracy while performing the geospatial interpolation, it does not matter that much in this case, as we would again need to bias-correct the CMIP5 climatic models with respect to bias-corrected ERA5 data.

The interpolated CMIP5 data were then bias-corrected using calibrated ERA5 data. It is to be noted that the daily data from CanESM2, GFDL-ESM2M, GISS-E2-H, IPSL-CM5A-MR, IPSL-CM5A-MR and NorESM1-M have no leap year (i.e., all years are 365 days in length).

In Figure 2, we have compared kernel density plots (Silverman, 1986; Sheather and Jones, 1991) of the Port Vila station-based data, uncorrected ERA5, calibrated ERA5, uncorrected CMIP5 and bias-corrected CMIP5 yearly rainfall data for each of the CMIP5 models. Visually, the calibration of ERA5 and the bias correction of CMIP5 models look promising with respect to station-based rainfall data (Figure 2). For a better comparison between each of the rainfall datasets, yearly maximum rainfall was analysed (Figure 2). This comparison was repeated for the six other locations in Table 1, and we observed a similarity between the station data, the calibrated ERA5 data and the bias-corrected CMIP5 rainfall datasets.

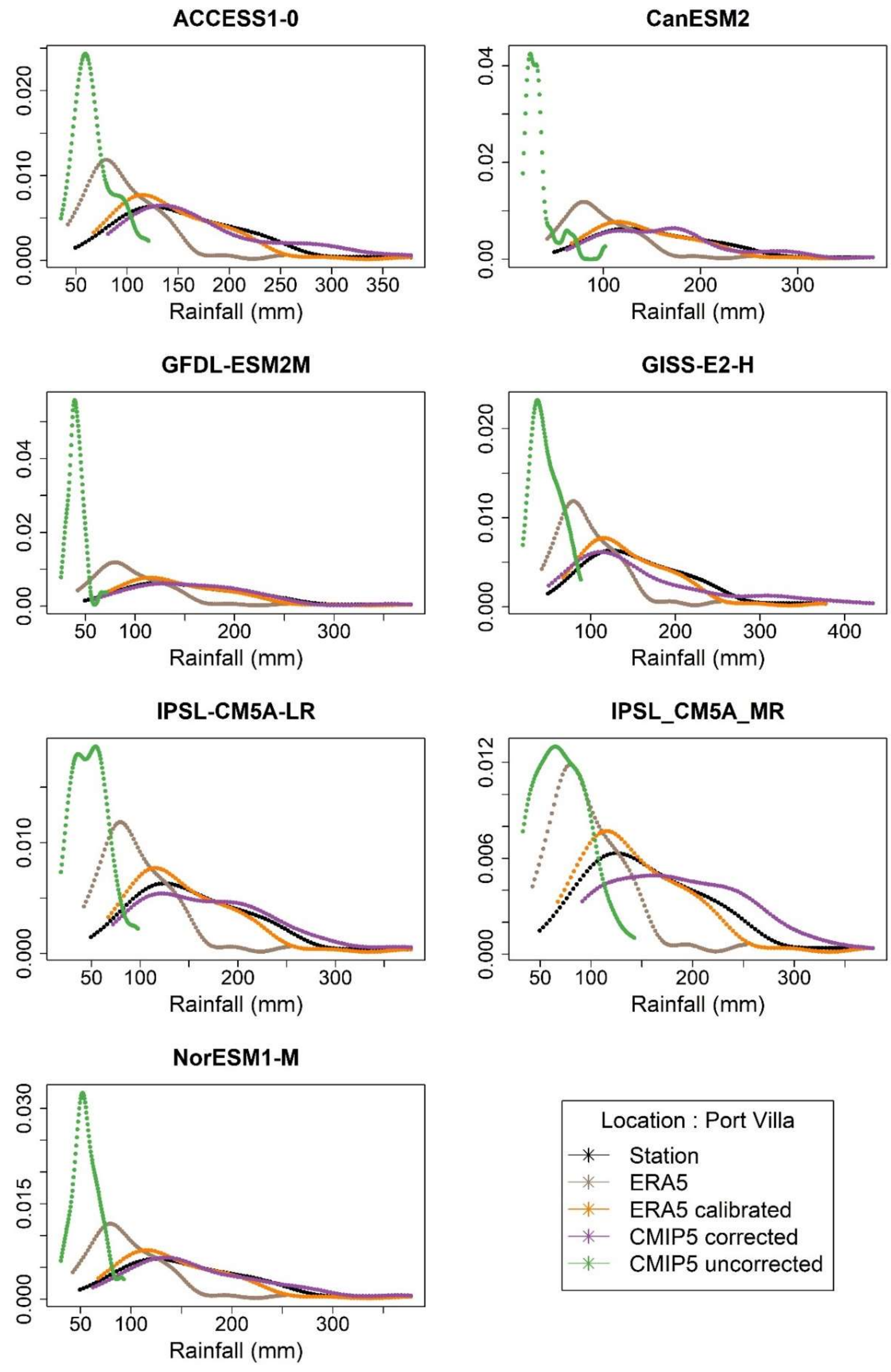


Figure 2. Comparison of kernel density graphs of daily rainfall data from 1961 to 2005 at Port Vila (168.32 E, 17.74 S) for the weather station data (black), raw ERA5 data (brown), calibrated ERA5 data (orange), uncorrected CMIP5 data (violet) and bias-corrected CMIP5 rainfall data (green). A close match between the black, orange and purple curves indicates that calibration of ERA5 data and bias-correction of CMIP5 data are performing well.

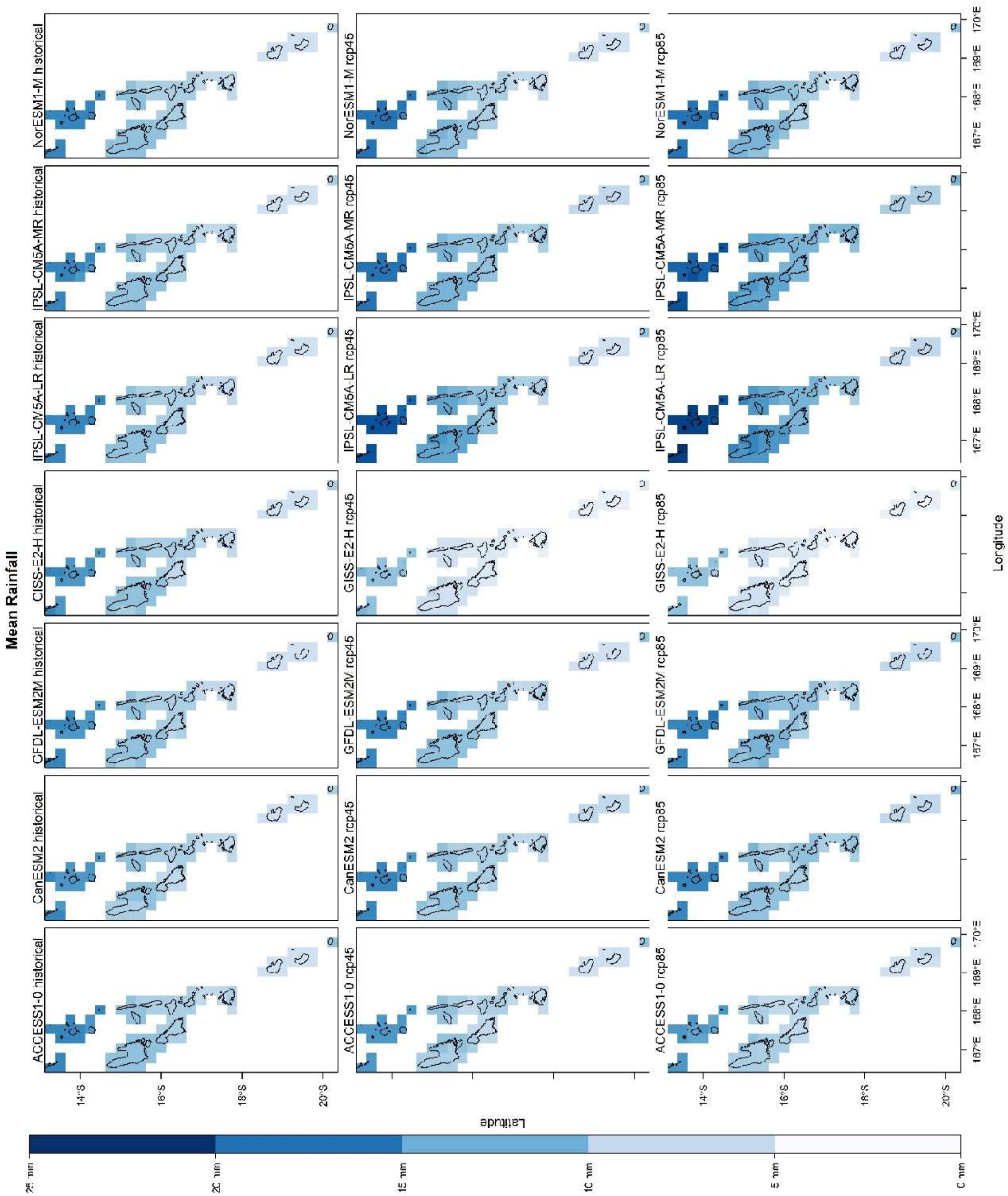


Figure 3. Climatological average daily rainfall for historical (1961 - 2005), RCP4.5 (2006 - 2100) and RCP8.5 (2006 - 2100) simulations from bias-corrected CMIP5 Models.

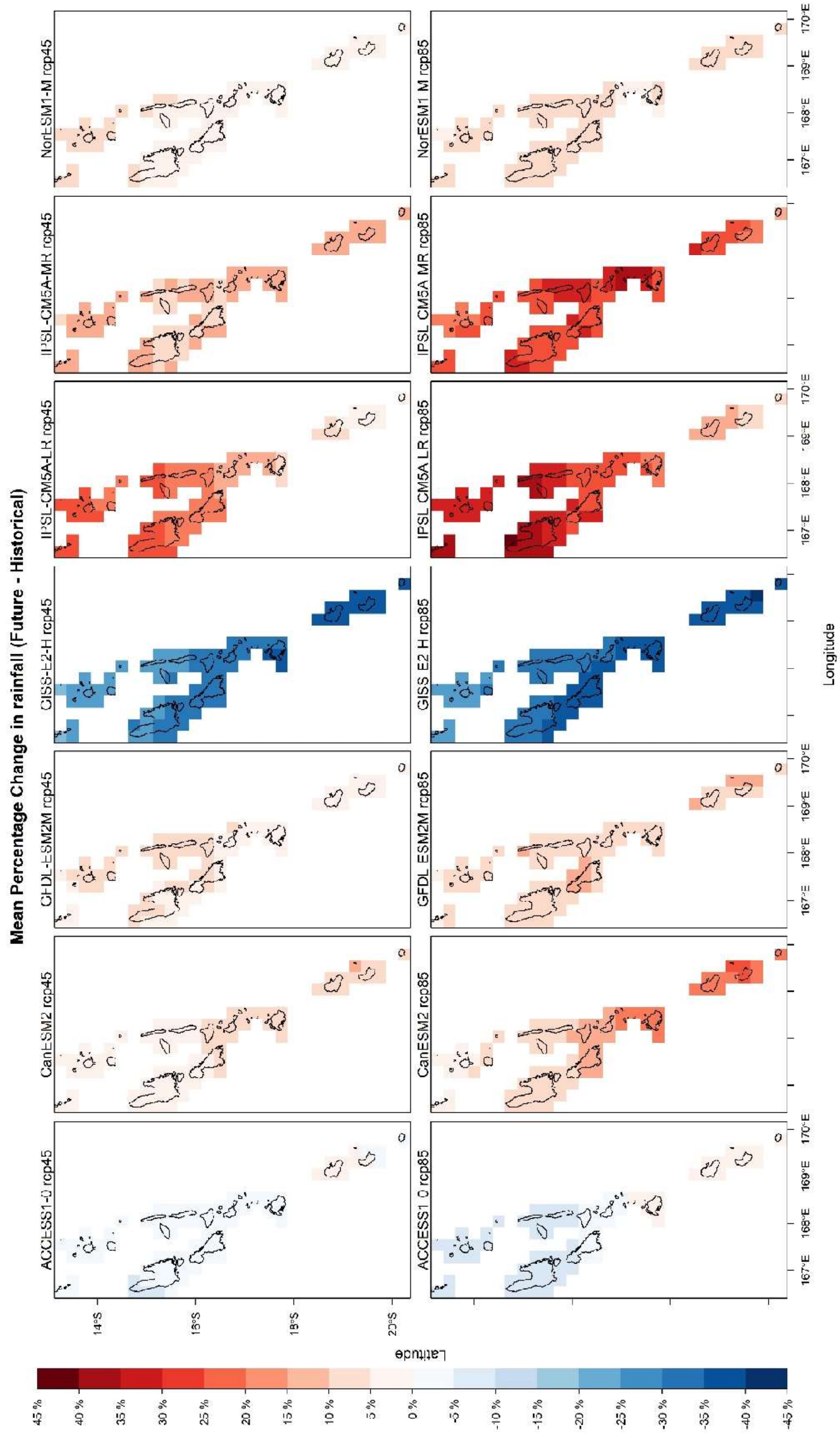


Figure 4. Mean percentage change in daily rainfall between historical (1961 – 2005) and future (2006 - 2100) simulations from bias-corrected CMIP5 Models.

To examine the bias-corrected historical, RCP4.5 and RCP8.5 CMIP5 rainfall dataset, we have calculated the climatological means for 1961 – 2005, 2006 – 2100 RCP4.5 and 2006 – 2100 RCP8.5, respectively, over Vanuatu (Figure 3). Percentage changes in daily rainfall between historical and future scenarios have also been calculated (Figure 4). Mean daily rainfall decreases in 5 of the 7 models. As the bias-corrected CMIP5 model dataset was based on the calibrated ERA5 dataset, the patterns persisted in the CMIP5 rainfall dataset as well.

Extreme value analysis of rainfall

For extreme value analysis, we selected the two locations, Luganville, Espiritu Santo (167.22 E, 15.52 S) and Port Vila, Efate (168.32 E, 17.74 S), as examples. First, the daily bias corrected CMIP5 rainfall values were extracted for these two locations (see Figure 5) and then the annual maximum daily rainfall was computed.

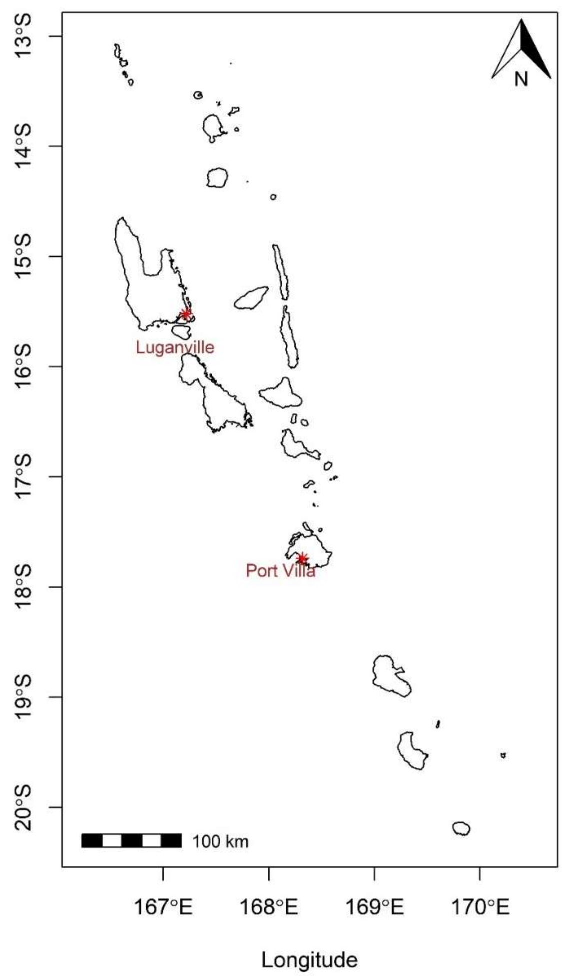


Figure 5. Map of Vanuatu showing the two locations, Luganville (167.22 E, 15.52 S) and Port Vila (168.32 E, 17.74 S).

We then computed the average recurrence interval (ARI) for various return periods. Three different periods (see Table 4) were used to compute the ARI values for 10-, 50- and 100-year return periods.

Table 4. Baseline periods for various CMIP5 scenarios

Baseline Period	Historical	RCP8.5	RCP4.5
1970 – 2000	X		
2040 – 2070		X	X
2070 – 2100		X	X

The Gumbel distribution was used for fitting the ARI curves (Figures 6 and 7). A previous study found the Gumbel distribution to be a very good fit for ARI curves (Mudashiru et al., 2023). Results are shown for each of the seven CMIP5 models, as well as the multi-model average (Doblas-Reyes et al., 2003; Donat et al., 2010).

The multi-model results for Port Vila and Luganville indicate a general increase in extreme rainfall intensity for a given return period, with larger increases for RCP8.5 than RCP4.5, and larger increases for 2070-2100 than 2040-2070. There is some variability between the individual climate model projections for extreme rainfall, so the projections should be treated with caution. For all return periods, the multi-model mean results for Port Vila show an increase of about 21% for 2040-2070 RCP4.5, 30% for 2070-2100 RCP4.5, 40% for 2040-2070 RCP8.5 and 70% for 2070-2100 RCP8.5. For all return periods, the multi-model mean results for Luganville show an increase of about 18% for 2040-2070 RCP4.5, 27% for 2070-2100 RCP4.5, 26% for 2040-2070 RCP8.5 and 57% for 2070-2100 RCP8.5.

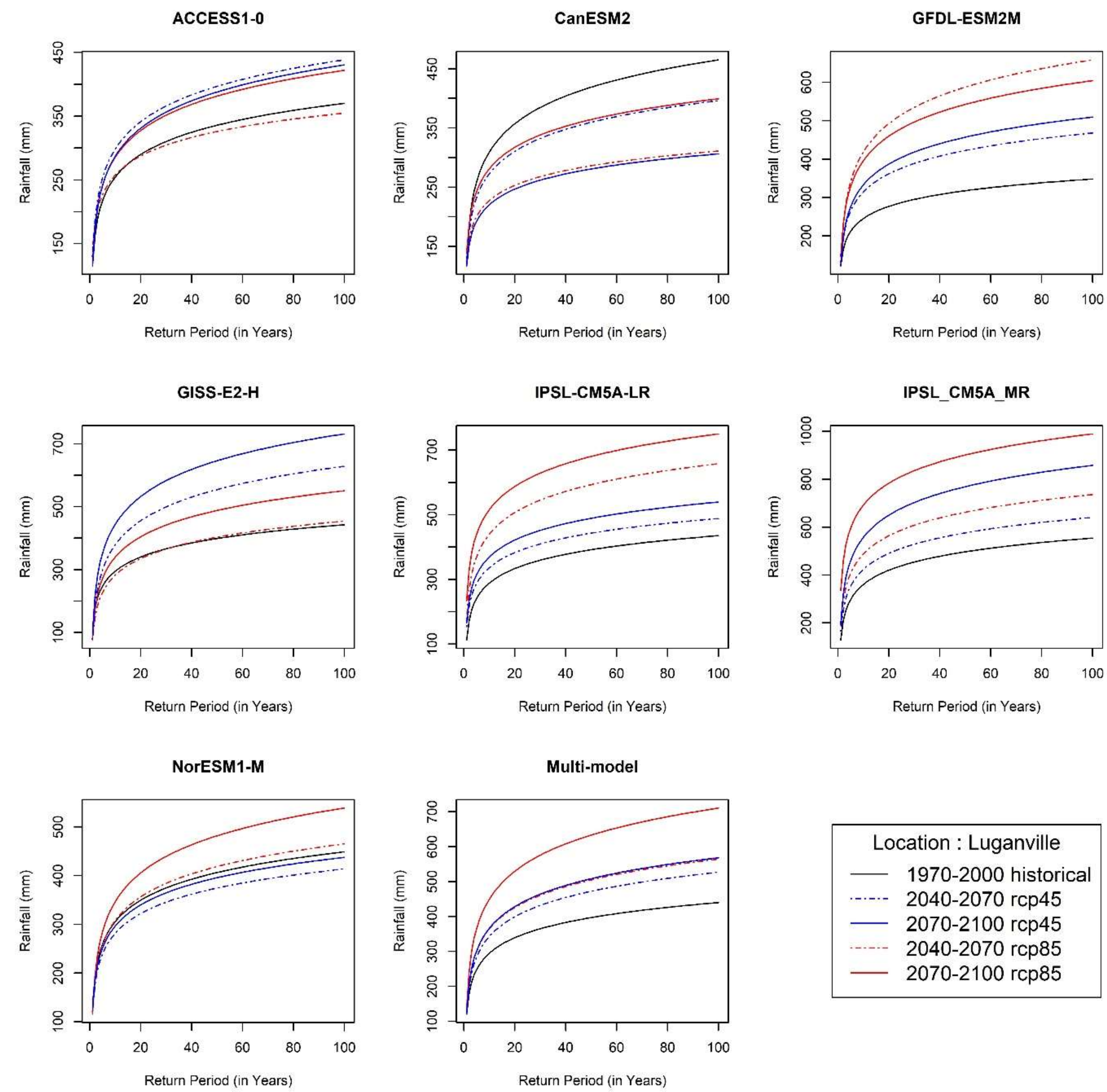


Figure 6. Average recurrence interval (ARI) curves of yearly maximum rainfall for Luganville (167.22 E, 15.52 S) using the Gumbel extreme value distribution. Comparison with historical 1970 – 2000 (black), RCP 4.5 2040 – 2070 (blue dashed) RCP 4.5 2070 – 2100 (blue), RCP 8.5 2040 – 2070 (red dashed) and RCP 8.5 2070 -2100 (red) has been shown for seven climate models and the multi-model average. The multi-model mean indicates an increase in extreme rainfall intensity for a given return period.

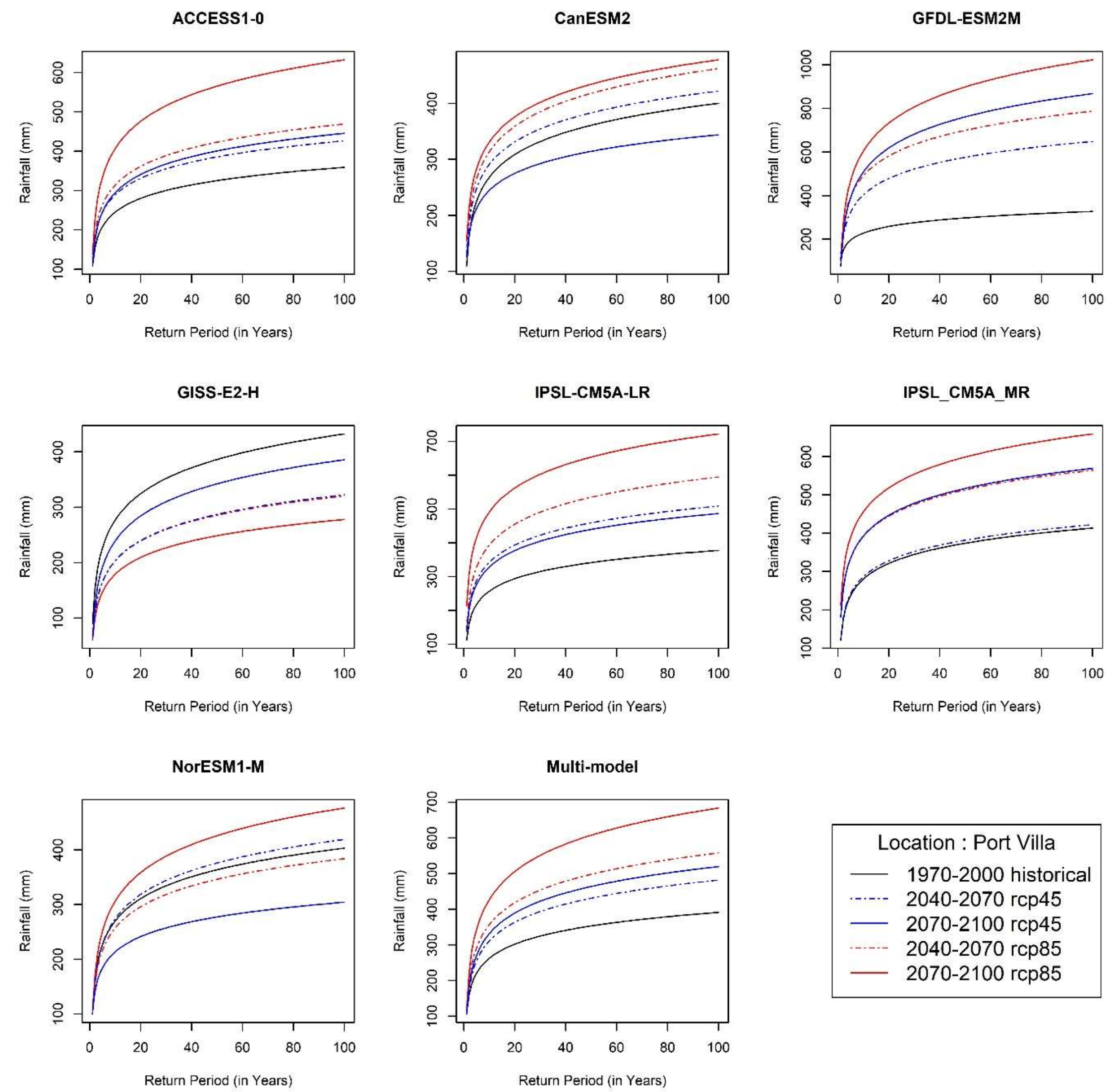


Figure 7. Average recurrence interval (ARI) curves of yearly maximum rainfall for Port Vila (168.32 E, 17.74 S) using the Gumbel extreme value distribution. Comparison with historical 1970 – 2000 (black), RCP 4.5 2040 – 2070 (blue dashed) RCP 4.5 2070 – 2100 (blue), RCP 8.5 2040 – 2070 (red dashed) and RCP 8.5 2070 -2100 (red) has been shown for seven climate models and the multi-model average. The multi-model mean indicates an increase in extreme rainfall intensity for a given return period.

2. Tropical cyclones

Tropical cyclone data

The observational tropical cyclone (TC) data were sourced from the South Pacific Enhanced Archive of Tropical Cyclones database (SPEArTC) (Diamond et al., 2012), where the best track data are mostly available at 6-hour intervals for the entire TC lifecycle. The wind speed for each TC is the maximum 10-minute sustained wind speed in knots (Diamond et al., 2012) that was converted to m/s using the conversion 1 knot = 0.51 m/s. Cyclones were also categorised according to the conventional definition of Southern Hemisphere TC season, *i.e.*, from 1st July to 30th June of the following year, with the following year representing a particular TC season, e.g. 1 July 2022 to 30 June 2023 is defined as the 2023 TC season.

The modelled TC data were obtained from Chand et al. (2017) and Bell et al. (2019), where they used a suite of climate models from the Coupled Model Intercomparison Project phase 5 (CMIP5) dataset (Taylor et al., 2012) to simulate TCs using the Okubo-Weiss-Zeta (OWZ) detection and tracking scheme (Tory et al., 2013a; Tory et al., 2013b). Both studies evaluated two scenarios: (1) the current-climate simulation (1970–2000) and (2) the future-climate simulation (2070–2100) under a high emissions pathway (RCP8.5). These datasets also included 850-hPa wind speeds that were converted to surface winds using a conversion factor of 0.8 (Franklin et al., 2003). We evaluated simulated TC tracks from 13 models (Table 5) for both historical and future scenarios.

Table 5. List of 13 CMIP5 models used for TC wind speed analysis along with time periods for the historical and future (RCP8.5) scenarios, based on data availability.

Models	Historical period	RCP8.5 period
SPEArTC	1970–2000	
ACCESS1.0	1970–2000	2070–2100
ACCESS1.3	1970–2000	2070–2100
BCC-CSM1.1	1970-2000	2069–2099
BCC-CSM1.1M	1970–2000	2070–2100
CCSM4	1970–2000	2070–2100
CNRM-CM5	1970–2000	2070–2100
CSIRO-MK3.6	1970–2000	2070–2100
GFDL-CM3	1970–2000	2070–2100
GFDL-ESM2G	1970–2000	2070–2100
GFDL-ESM2M	1970–2000	2070–2100
HadGEM2-ES	1970–2000	2069–2099
MIROC5	1970–2000	2070–2100
MRI_CGCM3	1970–2000	2070–2100

Data mining and quality control

Three buffer regions (Figure 8) were created (50 km, 250 km and 500 km) around all of Vanuatu, followed by a 500 km buffer around each province. These three buffers were used to extract TC tracks from all three datasets (*i.e.*, SPEArTC, 13 historical simulations and 13 RCP8.5 simulations) for the whole Vanuatu region, as well as for each province using the 500 km buffer. The extracted data were then quality-checked, ensuring that all TC track points (6-hour timestep for SPEArTC and 12-hour for CMIP5 models) within each buffer were extracted. For cases where a TC track traversed the buffer region but without a 6-hour (for SPEArTC) or 12-hour (for climate models) timestep, a timestep was estimated (especially for the 850-hPa TC wind speed) via a simple interpolation.

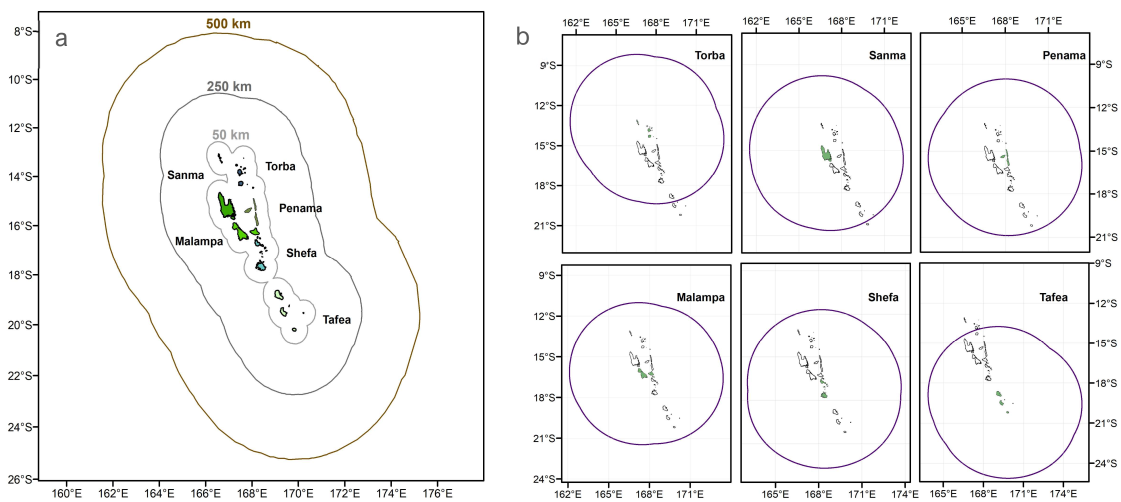


Figure 8. (Panel a) Map of Vanuatu along with the three buffers (50 km, 250 km and 500 km) used to extract TC tracks. Panel b shows a 500 km buffer around each province.

Statistical calibration

The TC wind speeds extracted from the climate models were calibrated so that the reconstructed data resembled the observed data as closely as possible. This was achieved using quantile matching with the help of a cubic spline approach, as discussed above. The 13 CMIP5 climate models (Table 6) for historical and RCP8.5 scenarios were calibrated with respect to the observational data (SPEArTC) (Figure 9). A bin size of 10 was determined using the Root Mean Square Estimate (RMSE) (Biswas et al., 2022).

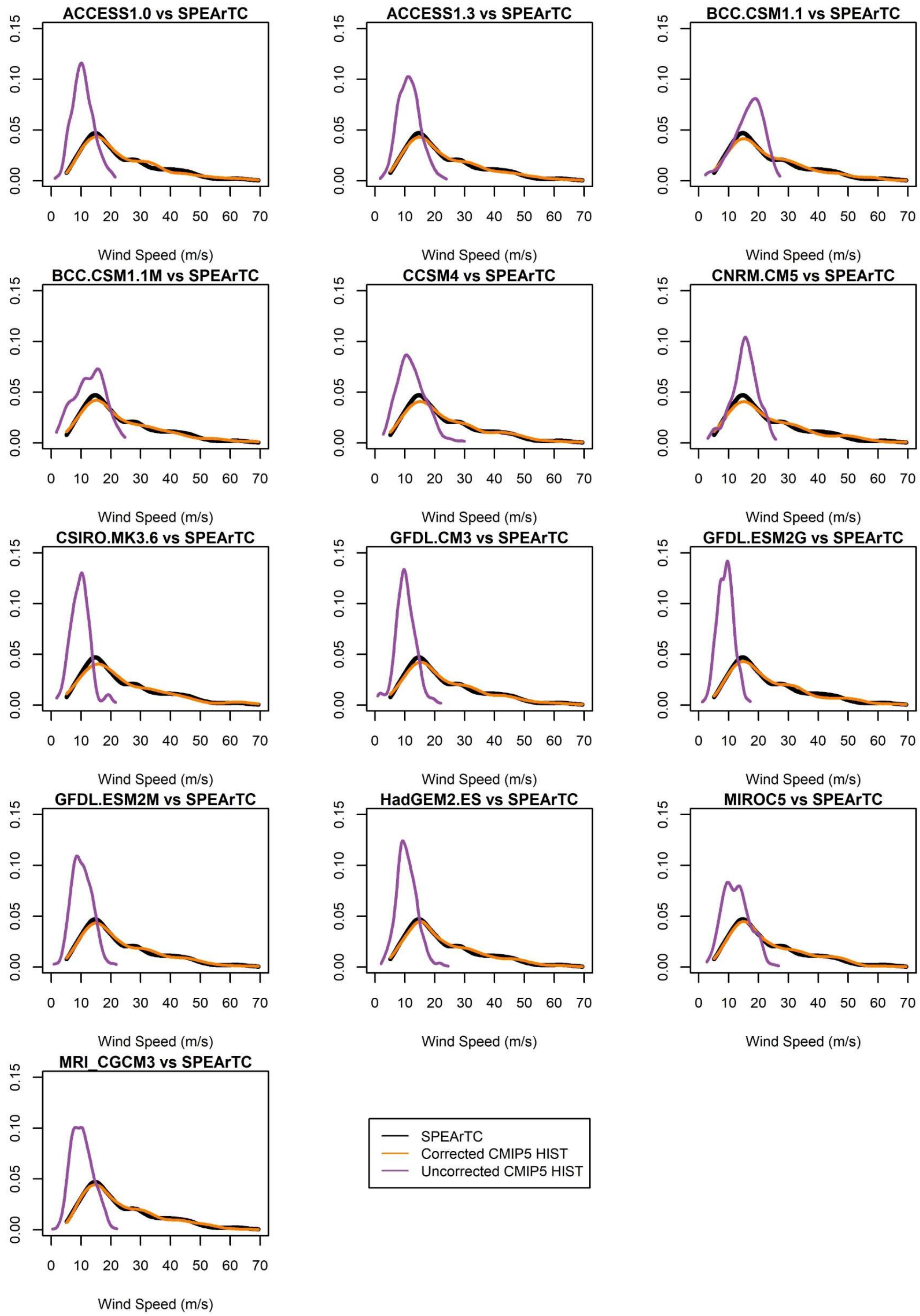


Figure 9. Kernel density graphs of TC wind speed data for 1970-2000 (within the 500 km buffer) using the cubic spline method. Each graph illustrates the observed data (SPEArTC in black), uncorrected CMIP5 data (purple) and bias-corrected model data (orange). A close match between the SPEArTC data and corrected CMIP5 data indicates that the calibration method is performing well.

Temporal analyses

The calibrations applied to the historical climate model data were also applied to the future climate model data. This bias-corrected dataset was then used to collate TC intensity information for each province, followed by a quality check, as mentioned above. TCs with wind speed reaching 17.5 m/s during 1970–2000 (representing the late 20th century) and 2070–2100 (late 21st century) were considered for further analyses. For two models, BCC-CSM1.1 and HadGEM2-ES, their late 21st century period is 2069–2099 (see Table 5).

An additional step was taken to identify the best-performing models because Bell et al. (2019) highlighted some caveats associated with the outputs from the OWZ TC detector. Their study showed that the TC detection scheme sometimes tends to underestimate or overestimate TC frequency, potentially impacting the projection assessments. Bell et al. (2019) objectively defined specific measures to eliminate errors and achieve a more accurate climatology. We used one such definition: the number of simulated TCs should be within ± 50% of the TC counts in SPEArTC (*i.e.*, the observed climatology). Using this criterion, eight best-performing models were selected for all analyses in this study (Table 6). These eight models were also identified as the best-performing models by Chand et al. (2017).

Table 6. Total number of TCs extracted within each buffer for all 13 CMIP5 models (both historical and RCP8.5). The bold TC numbers indicate the best-performing models that simulated at least 50% of total observed TCs from SPEArTC.

Climate models	Historical TCs			RCP8.5 TCs		
	500 km	250 km	50 km	500 km	250 km	50 km
SPEArTC	105	73	40			
ACCESS1.0	**69**	**51**	**27**	73	49	27
ACCESS1.3	**82**	**57**	**33**	124	90	46
BCC-CSM1.1	**51***	**24***	**14***	42	24	12
BCC-CSM1.1M	41	24	8	49	26	9
CCSM4	41	35	19	32	22	13
CNRM-CM5	27	18	10	17	10	4
CSIRO-MK3.6	32	19	11	73	48	33
GFDL-CM3	42	30	20	31	17	4
GFDL-ESM2G	**57**	**34***	**10***	41	24	10
GFDL-ESM2M	**59**	**36***	**17***	44	23	9
HadGEM2-ES	**80**	**53**	**32**	55	31	14
MIROC5	**89**	**52**	**29**	53	33	16
MRI-CGCM3	**109**	**65**	**42**	91	63	41

***** Even though this model's climatology is not within ±50% of SPEArTC, either/or it's very close, and has been identified as a best performing model by Chand et al. (2017); hence, it was included for further analyses.

For all analyses, we used the maximum TC wind speed along the TC track within the buffer as our emphasis is on extremes. We evaluated the TC climatology as per the observational data (time-series for the 1971–2021 TC season) at the national and provincial levels. Projected changes in TC intensity and frequency from the selected models were assessed in two ways (both at national and provincial levels): firstly, by evaluating “All TCs” (from categories 1 to 5) and secondly, only considering “Severe TCs” (categories 3 to 5). TCs were sorted into respective categories using the Australian TC intensity scale (Table 7). In both cases, TC intensities and TC frequencies were analysed between the current and future climate conditions. Consequently, projected changes in these TC metrics (frequency and intensity) were derived by computing their percentage changes. The Gumbel function was used to construct ARIs. We also combined the eight models to form a multi-model average and performed similar analyses.

Table 7. TC classification is based on the Australia/Fiji intensity scale. Maximum wind refers to the 10-minute sustained windspeed.

Category	Maximum wind (km/hr)
1	63 – 88
2	89 – 117
3	118 – 159
4	160 – 200
5	> 200

Projected changes in TC frequency and intensity

The projected changes in TC frequency and TC intensity are shown in Figure 10 for the two provinces. Out of eight models, six and seven models demonstrate a projected decrease in TC frequency in the future climate for Shefa and Sanma provinces, respectively (Figure 10, left panel). Conversely, TC intensities are projected to increase at both locations, indicated by seven (for Shefa) and six (for Sanma) models (Figure 10, right panel).

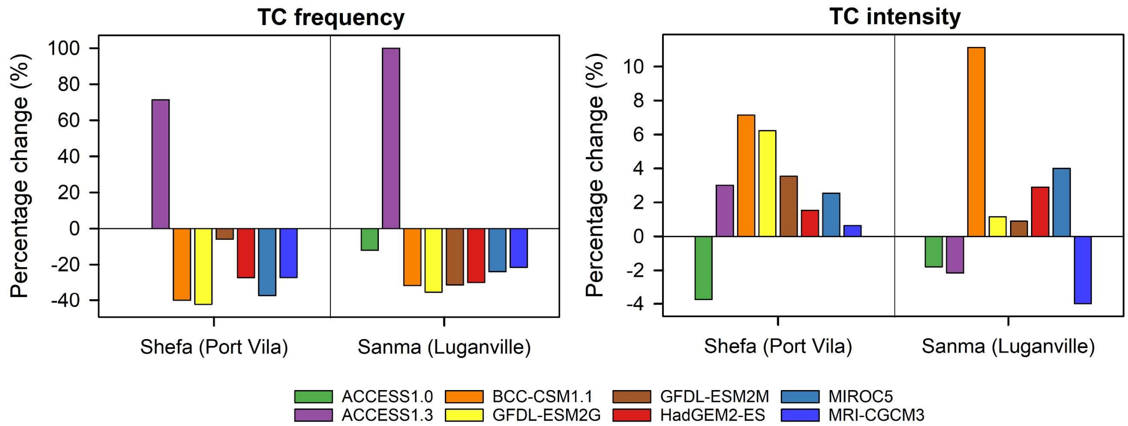


Figure 10. Percentage change in mean TC frequency (left panel) and TC intensity (right panel) between the current and future climate conditions for the eight CMIP5 models. These projections are for Shefa (city: Port Vila) and Sanma (city: Luganville) provinces (labelled on horizontal axes). Most models indicate a decline in TC frequency and an increase in TC intensity in the future climate for both cities.

Intensity-frequency curves

Two example curves for TC intensity-frequency changes between historical and future periods are shown below for two provinces: Shefa (which includes Port Vila; Figure 11) and Sanma (which includes Luganville; Figure 12). Most models simulate an increase in extreme windspeeds. The multi-model average for Shefa indicates that the increase is about 6% for all return periods (Figure 13, top row). The multi-model average for Sanma indicates that the increase is about 3% for all return periods (Figure 13, bottom row).

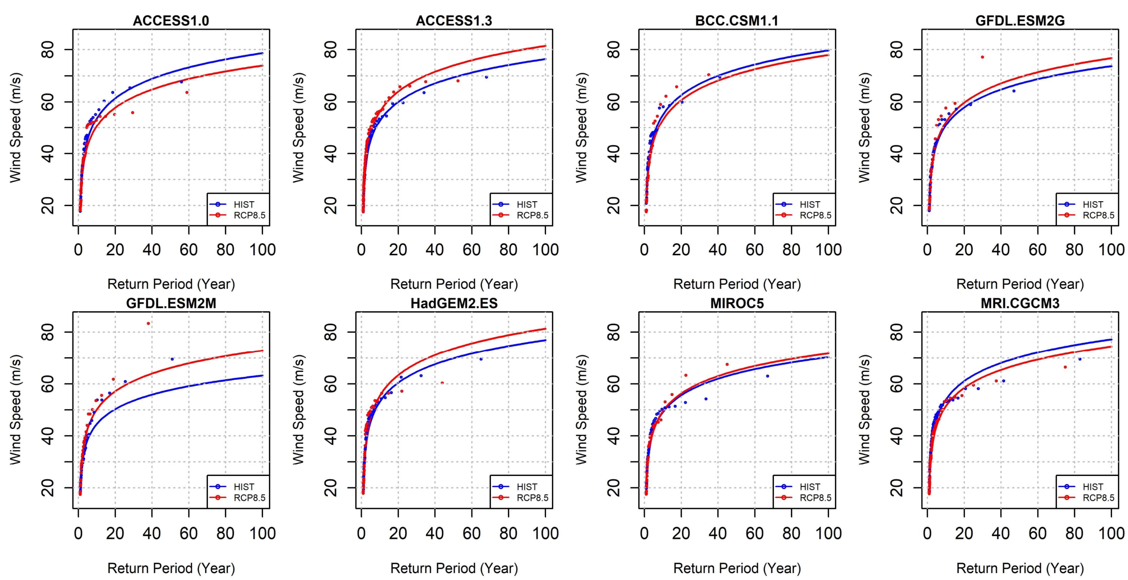


Figure 11. Average intensity-frequency curves of maximum TC wind speed intensity for Shefa province (city: Port Vila). Comparisons are for historical 1970 – 2000 (blue) and RCP 8.5 2070 – 2100 (red) cases. Five out of eight models simulate an increase in extreme windspeed.

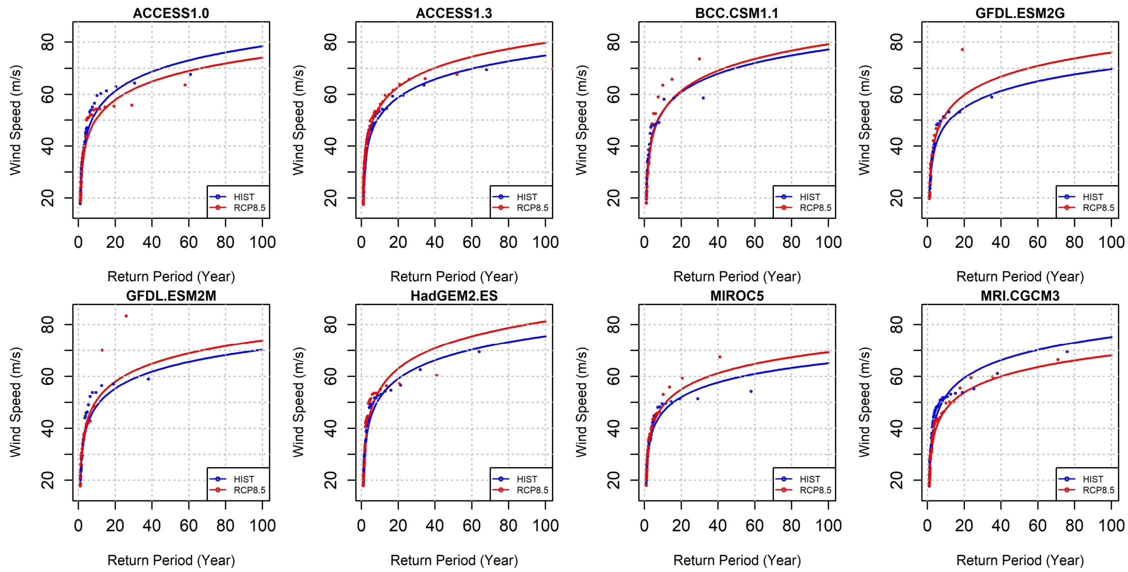


Figure 12. As in Figure 11, but for Sanma Province (city: Luganville). Six out of eight models simulate an increase in extreme wind speed.

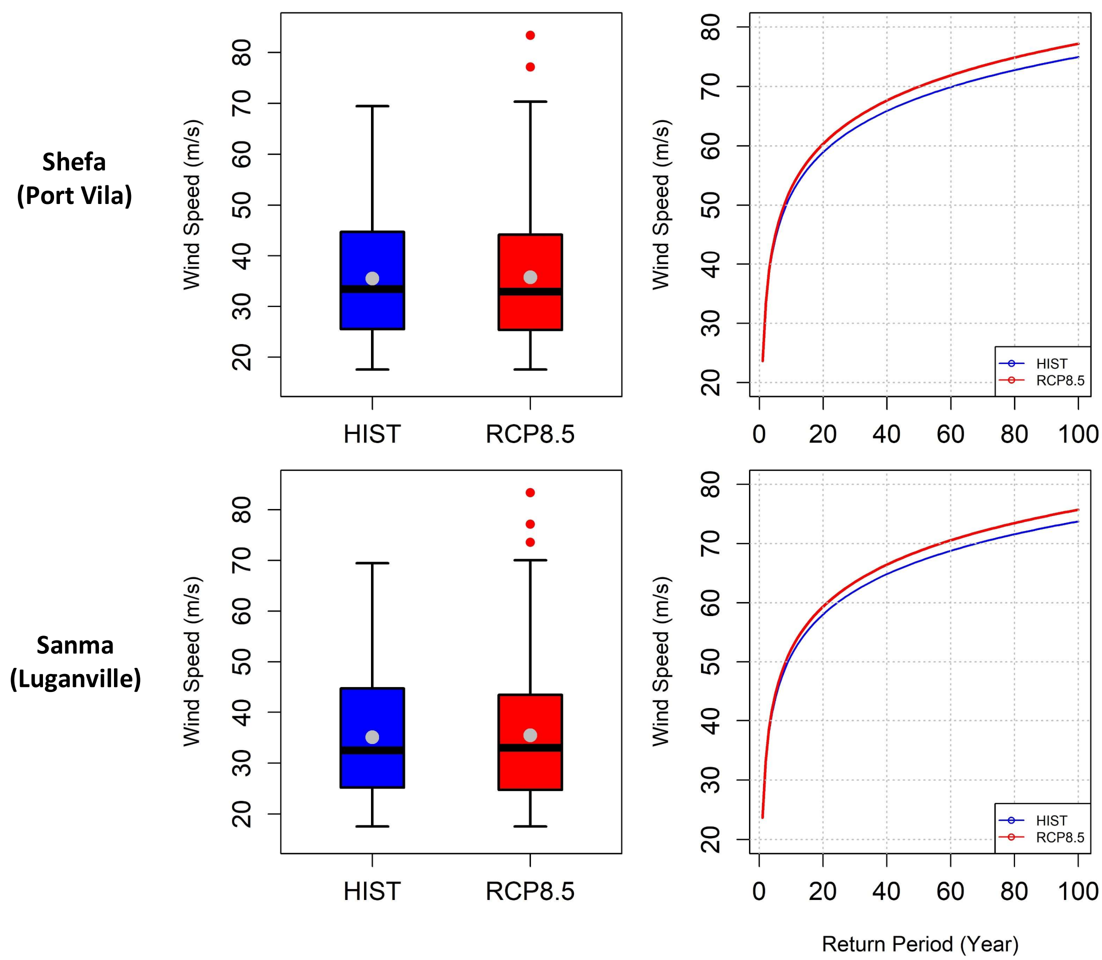


Figure 13. TC wind speed distribution (left) and ARIs (right) of all eight models combined to form a multi-model average for Shefa (city: Port Vila; top row) and Sanma (city: Luganville; bottom row) provinces. The multi-model average at both locations shows an increase in extreme wind speed.

Discussion

In this study, we assessed projected changes in extreme rainfall and windspeed for Vanuatu.

We have used ARI curves to show the projected change in annual maximum daily rainfall for 2040-2070 and 2070-2100 for low and high emission scenarios. A general increase in extreme rainfall intensity is simulated for both Port Vila and Luganville. There are some differences in ARI curves between climate models. For example, GISS-E2-H shows a decrease in extreme rainfall intensities at Port Villa while CanESM2 shows a decrease at Luganville. So, the return period values should be interpreted with caution. The extreme rainfall data can be used in current and future flood risk assessments. New Zealand NIWA is undertaking an ADB-sponsored flood risk assessment for Luganville that incorporates our extreme rainfall projections and overlays an exposure database that includes buildings and infrastructure. This will inform adaptation planning.

We also used ARI curves to assess projected changes in TC windspeeds. Assessing the vulnerability of a specific region to TCs is an essential step in formulating enhanced strategies for disaster preparedness. We investigated the potential impact of anthropogenic greenhouse warming on the frequency and intensity of TCs, specifically for the Vanuatu region (including all six provinces).

Overall, the projections indicated a decline in TC frequencies; however, TCs will likely have enhanced intensities in the future scenario relative to the current climate – consistent with previous findings (Tory *et al.*, 2013; Walsh *et al.*, 2016; Chand *et al.*, 2017; Bell *et al.*, 2019; Knutson *et al.*, 2020; CSIRO and SPREP, 2021). Projections derived from the other two buffers (*i.e.*, 250 km and 50 km) revealed consistent trends, adding more lines of evidence to support our findings. It is worth mentioning that the consensus found in these other studies was generally for the broader South Pacific area. However, our findings offer additional evidence concerning the projections of both frequency and intensity of TCs for Vanuatu, and all its six provinces, exclusively.

The results from provincial analyses were insightful, given that they demonstrated the hazards different regions are likely to encounter due to TCs when approaching the end of the 21st century. For instance, the 6% increase in intensity derived at Port Vila (within Shefa province in central Vanuatu) is larger than the 3% increase at Luganville (northwestern side within Sanma province).

The information gained from these projections is important regarding adaptation and planning. Port Vila and Luganville are the most populous areas with the largest number of buildings and infrastructure, thus incurring the greatest loss and damage from TCs, including critical infrastructure, disruption of livelihoods, threats to water and food security, compromising health and affecting education. One study estimated that 5145 buildings in Luganville and 2115 buildings in Port Vila are at risk of heavy damage from an extreme wind event with a 100-year return period (Beca, GNS and NIWA, 2016). UN.ESCAP (2021) has indicated that Vanuatu's expenses (approx. USD 1.1 billion) sustained from natural disasters could increase to USD 1.4 billion in a worst-case scenario (RCP8.5), which can risk the country losing about 20% of its annual gross domestic product. Hence, relevant agencies (e.g., Meteorological Services, National Disaster Management Offices and Departments of Climate Change) must utilise this information efficiently to enhance the adaptation and planning process. It is also crucial that this information is clearly communicated to sector stakeholders and the wider community through their information products and awareness programmes.

Conclusions

Extreme daily rainfall is expected to increase in future due to climate change. Historical weather station data, reanalysis data, seven climate model simulations and extreme value analysis were combined to estimate current and future extreme rainfall for Port Vila and Luganville. The current baseline was defined as 1970-2000, while the future periods were 2040-2070 and 2070-2100. Low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenarios were considered. For extreme daily rainfall with return periods of 10-100 years, the multi-model mean results for Port Vila showed an increase of about 21% for 2040-2070 RCP4.5, 30% for 2070-2100 RCP4.5, 40% for 2040-2070 RCP8.5 and 70% for 2070-2100 RCP8.5. For return periods of 10-100 years, the multi-model mean results for Luganville showed an increase of about 18% for 2040-2070 RCP4.5, 27% for 2070-2100 RCP4.5, 26% for 2040-2070 RCP8.5 and 57% for 2070-2100 RCP8.5. These increases have significant implications for future flood risk management strategies.

Although Vanuatu is experienced in responding to cyclones, a double event such as TC Judy and TC Kevin in March 2023 presented unprecedented challenges. Tropical cyclones are projected to become less frequent in future, but the average intensity is projected to increase. Therefore, developing a more comprehensive understanding of cyclone behaviour is essential to inform adaptation strategies across different sectors. Such understanding can also enhance the general public's resilience to the destructive impacts of extreme events, particularly in a worst-case scenario. Reanalysis data, eight climate model simulations and extreme value analysis were combined to estimate current and future extreme windspeeds for Port Vila and Luganville. The current baseline was defined as 1970-2000, while the future period was 2070-2100. A high (RCP8.5) greenhouse gas emissions scenario was considered. For extreme TC windspeed with return periods of 10-100 years, the multi-model mean results showed an increase in the intensity of about 6% for Port Vila and 3% for Luganville. These increases have implications for future cyclone risk management strategies.

Additionally, decision-makers such as environmental managers and city planners can use these projections along with suitable exposure and vulnerability to undertake detailed risk assessments in Vanuatu. This can facilitate more effective adaptation strategies across various sectors, complementing previous findings (e.g., Beca, GNS and NIWA, 2016).

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Annex G – Technical Report: Van-KIRAP Rainfall Projections

Model Name	Port Villa														
	Comparison with Historical(1970-2000)														
	RCP 4.5 (2040-2070)				RCP 4.5 (2070-2100)				RCP 8.5 (2040-2070)				RCP 8.5 (2070-2100)		
	10-year	50-year	100-year		10-year	50-year	100-year		10-year	50-year	100-year		10-year	50-year	100-year
Multi-Model	18.43%	22.05%	23.08%		26.32%	31.35%	32.78%		35.90%	41.05%	42.52%		63.04%	72.49%	75.17%
ACCESS1-0	17.90%	18.49%	18.66%		20.15%	23.16%	24.02%		28.04%	30.01%	30.58%		65.88%	73.72%	75.98%
CanESM2	8.50%	6.14%	5.48%		-8.77%	-12.90%	-14.07%		16.93%	15.78%	15.46%		23.39%	20.28%	19.40%
GFDL-ESM2M	76.94%	93.30%	98.13%		122.85%	155.51%	165.16%		115.27%	134.79%	140.56%		165.02%	201.66%	212.49%
GISS-E2-H	-26.47%	-25.62%	-25.39%		-13.56%	-11.37%	-10.78%		-26.60%	-26.04%	-25.88%		-34.83%	-34.99%	-35.03%
IPSL-CM5A-LR	33.26%	34.47%	34.82%		27.89%	28.72%	28.96%		53.16%	56.61%	57.60%		91.21%	91.38%	91.43%
IPSL-CM5A-MR	2.17%	2.15%	2.15%		40%	38.22%	37.71%		39.54%	37.20%	36.52%		62.47%	60.11%	59.43%
NorESM1-M	1.45%	3.43%	3.99%		-20.92%	-23.71%	-24.51%		-4.78%	-4.78%	-4.78%		13.42%	17.16%	18.22%

Model Name	Port Resolution														
	Comparison with Historical(1970-2000)														
	RCP 4.5 (2040-2070)				RCP 4.5 (2070-2100)				RCP 8.5 (2040-2070)				RCP 8.5 (2070-2100)		
	10-year	50-year	100-year		10-year	50-year	100-year		10-year	50-year	100-year		10-year	50-year	100-year
Multi-Model	25.24%	29.59%	30.78%		22.09%	25.46%	26.37%		43.18%	48.75%	50.27%		76.10%	86.20%	88.95%
ACCESS1-0	47.69%	51.07%	52.01%		8.12%	8.88%	9.09%		34.65%	36.50%	37.02%		29.26%	32.46%	33.35%
CanESM2	29.96%	32.86%	33.64%		-2.13%	-3.55%	-3.93%		29.73%	31.01%	31.35%		70.35%	74.76%	75.94%
GFDL-ESM2M	34.91%	39.27%	40.46%		45.95%	52.02%	53.67%		87.08%	96.15%	98.63%		110.72%	120.77%	123.51%
GISS-E2-H	-54.61%	-56.69%	-57.25%		-26.92%	-25.74%	-25.43%		-37.73%	-38.59%	-38.81%		-49.44%	-50.65%	-50.97%
IPSL-CM5A-LR	14.01%	14.08%	14.10%		9.56%	8.77%	8.56%		55.29%	58.90%	59.86%		118.39%	125.84%	127.84%
IPSL-CM5A-MR	70.01%	73.89%	74.95%		98.14%	100.09%	100.63%		102.80%	108.49%	110.05%		143.99%	143.45%	143.31%
NorESM1-M	-1.24%	0.35%	0.81%		-20.53%	-23.91%	-24.88%		-11.08%	-12.99%	-13.54%		5.86%	8.32%	9.03%

Annex H – Training Mission Agenda and Schedule

Training Mission to Vanuatu by Rob Hardy
28 August 2023 – 9 September 2023
Proposed Agenda

Date		Time	Description
Sun	27 Aug		RPH arrives Vanuatu
Mon	28 Aug	09.00 - 10.00	**Opening Project Team Meeting** to agree detailed agenda and logistics for the 2 weeks
			attendees: Sunny, Raviky, Rob, Moirah
		10.30 – 17.00	**Feedback Meetings** with PWD/R4D2 staff to provide feedback on revised Vanuatu Road Design Guide (to be submitted mid-August)
			attendees: all technical managers and decision makers up to DG PWD
Tues	29 Aug	08.00 – 17.00	**Keep free** for RPH to incorporate feedback into final version of Vanuatu Road Design Guide and training presentations
Wed	30 Aug	09.00 – 10.30	**Orientation Presentation** - Vanuatu Road Design Guide. Introductory presentation of new design guide, key objectives and changes from 2017 VRRDG.
			attendees: all technical managers and decision makers up to DG PWD and including Minister if available, plus donor program staff
		10.30 – 13.00	**Keep free** for individual follow-up meetings
		13.00 – 16.00	**Technical Training Session 1 :** Changing climate impacts on road infrastructure
			Attendees for technical training sessions and design workshops : all technical staff likely to use updated Vanuatu Road Design Guide
Thu	31 Aug	09.00 – 11.30	**Training Session 2** : Road Design Process – the importance of surveys and rational design
		13.30 – 16.00	**Training Session 3** : Route Selection, Alignment and Cross-Section Design
Fri	01 Sep	09.00 – 11.30	**Training Session 4** : Drainage Design 1 – catchments, flows and water/road interfaces
		13.30 – 16.00	**Training Session 5** : Drainage Design 2 – drainage solutions, sizing and details
Sat	02 Sep	all day	**Free**
Sun	03 Sep	all day	**Free**

Mon	04 Sep	09.00 – 11.30	**Training Session 6** : Designing for Road Safety
		13.30 – 16.00	**Training Session 7** : Implementing Road Designs – the importance of applying standards for materials and workmanship
Tue	05 Sep	09.00 – 11.30	**Design Workshop Session 1** : work together to develop a road design using the updated Vanuatu Road Design Guide
		13.30 – 16.00	**Design Workshop Session 2** : continued
Wed	06 Sep	09.00 – 11.30	**Design Workshop Session 3** : continued
		13.30 – 16.00	**Design Workshop Session 4** : continued
		16.00 – 17.30	**Training Certificates** presented to all participants and informal discussions
Thu	07 Sep	08.00 – 12.00	**Training Feedback and Evaluations –** individual meetings with attendees
		12.00 – 17.00	**Keep free** for RPH to produce final versions of all documents and training evaluation report
Fri	08 Sep	09.00 – 10.00	**Closing Project Team Meeting** to review the project and training and agree any follow-up actions
			Attendees: Sunny, Raviky, Rob, Moirah
		10.00 – 11.00	**Formal Closeout Meeting and Handover of Project Deliverables to PWD**
			Attendees: Sunny, Moirah, Raviky, Rob and Senior PWD staff
Sat	09 Sep		RPH departs Vanuatu

7Dee Consult
5 Portia Road
Stratford upon Avon
CV37 0AR
United Kingdom

SPREP
Secretariat of the Pacific Regional Environment Programme