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TRANSPORT KNOWLEDGE NOTE

Supporting Road Network Vulnerability Assessments in Pacific Island Countries

In Pacific Island Countries, high vulnerability to the impacts of climate change and natural disasters means that such events can have devastating social and economic impacts when critical infrastructure is compromised.[1] This has been apparent in countries where severe disruptions to road networks have resulted in a loss of access to basic infrastructure and services. Building resilience is therefore a prerequisite for long-term sustainable development, and Governments will increasingly seek tools that can help guide investment and policy decisions by considering the effects of climate change and natural disasters. Among such tools are road network vulnerability assessments, which provide a means to design and maintain a climate resilient network. This article highlights the process and lessons learned from the Vulnerability Assessment and Climate Resilient Road Strategy of the Samoan road network, and outlines a replicable approach for small island nations with acute capacity challenges that seek to balance analytical rigor with the need for practicality.

Transportation Networks in Pacific Island Countries

In most countries, the transportation of people and goods is essentially completely facilitated by the road network. While inter-island transportation may be conducted via seaports and airports, the accessibility of the maritime and aviation transport still needs to be guaranteed by intra-island road networks. However, in some parts of the world, and

[1] In acknowledging that a variety of definitions may be used for the terms risk, hazard, vulnerability and exposure, the following definitions are used for this article. ***Risk*** refers to the likelihood that a bad outcome occurs to an exposed asset (e.g., bridge failure) within a specified period because of the effects of natural effects (e.g., tropical cyclone induced storm surge). ***Hazard*** refers to when the effects of the natural events reach or exceed specified levels at a certain location within a period (e.g., storm surge exceeding 1 meter). ***Vulnerability*** refers to the propensity of an asset to be damaged by the effects of an event. ***Exposure*** refers to when assets are in harm's way.

PHOTO CREDIT: WEST COAST ROAD, SAMOA. CONOR ASHLEIGH, WORLD BANK especially in Pacific Island Counties (PICs), the risk posed to transportation networks by geophysical and climate-related events such as earthquakes and tropical cyclones is relatively high and the impact can be severe. Such events can cause severe damage to infrastructure, particularly the transport network, and result in significant adverse effects on livelihoods and the loss of lives.

PICs have many common obstacles to building resilience for critical infrastructure. For example, land area is limited and infrastructure such as hospitals, schools, places of employment, tourist infrastructure, port facilities, power plants, and often airports, are located primarily within the coastal zone. The road networks are often not complex and have very few redundant paths; therefore, damage to a single road link or a bridge may completely interrupt communities access to crucial lifelines, such as airports or hospitals. In addition, most of the population also lives near the shoreline, and are largely served by coastal roads, meaning the reliability of these coastal road networks are critical in ensuring connectivity. Island ring roads are crucial for guaranteeing the daily movement of people and goods, however some sections of these roads are situated steps from the coast. The road networks, other infrastructure, and the communities that live along them are faced with a range of specific and severe vulnerability issues including: (i) exposure to sea-level rise, wave action during very high tides, storm surges, cyclones and tsunamis; (ii) flash flooding and landslides during extreme rainfall events; (iii) damage from earthquake ground motion; and, (iv) accelerated infrastructure deterioration due to extreme weather, aggressive salty environment and rising water tables. In addition, there is often limited capacity and resources compounded with many competing priorities, which limit the ability to undertake country (network) scale assessments to address such challenges.

Furthermore, the vulnerability of the transport network in PICs is expected to increase due to climate change, and where the frequency and/or intensity of climate and extreme weather events are projected to increase, so too will the impacts on coastal roads and other assets. Therefore, the challenge faced by many PICs is how to best enable the road sector to adapt the impacts of climate change and how to strategically plan for the impacts of climate change, accounting for future vulnerability issues, to better inform adaptation and resilience building efforts and ensure the sustainability of investments and development efforts. Mainstreaming climate adaptation into transport sector planning is therefore critical to ensuring that appropriate management solutions are provided to reduce climate risks for road sector assets and to build lasting climate resilience.

Since road networks are geographically distributed, varied in nature and are subject to a variety of hazards, many interventions could be possible to mitigate the risk of network failure; however, the selection process for the best strategy forward might not be immediately obvious to decision makers. Because budgets are often constrained, prioritization of interventions is needed that considers social and economic factors. An objective, defensible, transparent and repeatable approach to prioritizing all feasible alternative risk mitigation options is therefore necessary. Road network vulnerability assessments provide a means to achieving a comprehensive approach to effectively managing risks by (i) identifying the threats posed by geophysical and climate-related events (ii) assessing the risk of transport network failures (iii) assessing potential damage to network components (e.g., bridge and road links) and potential impacts to communities and economies; (iv) identifying potential measures to enhance the resilience of transport networks; and, (v) undertaking a cost-benefit analysis of potential measures to inform the prioritization of investments. This can help decision makers answer the question as to how one can establish and deliver a fit-for-purpose resilient road network.

THE SAMOAN ROAD NETWORK VULNERABILITY ASSESSMENT

In Samoa, a Vulnerability Assessment of the road network in Upolu and Savai'i (1150 kilometers) was undertaken to support the development of a Climate Resilient Road Strategy to provide a comprehensive assessment of and sector planning strategy for the national road network. This included identifying key hazards, assets and areas vulnerable to severe weather events, assessing the impacts of climate change, as well as analyzing current practices in network development, maintenance and asset management to outline strategies, and support the development of maintenance plans that, if implemented, would decrease the vulnerability of the road network. The work undertaken in Samoa is examined here to propose an approach that is appropriate and replicable in other PICs.

COUNTRY CONTEXT

Samoa is a small island developing state located in the Pacific Ocean and is highly vulnerable to the impacts of geophysical and climate related events. Past extreme events have caused severe damage to the infrastructure (particularly the transport network), severely impacted livelihoods, and resulted in the loss of lives. For example, Tropical Cyclone Evan, which struck Samoa in 2012, resulted in total estimated damage and loss equivalent to about 28 percent of the total value of goods and services produced in Samoa in 2011 (Government of Samoa, 2013).

The road network is of critical importance to the development of the country by providing access to economic activities and social services. However, vulnerability is high as approximately 70 percent of the population lives within one km of the coast, with key infrastructure located predominantly within the coastal zone. The islands of Upolu and Savai'i suffer regular breaks of serviceability due to vulnerable links or locations becoming impassable from flooding, debris deposit, and/or culvert, bridge and pavement damage. Expected climate change effects will further put these coastal assets and communities at a higher level of risk (Government of Samoa, 2017b). Constraints on financial and technical resources limit the capacity to effectively plan for, and proactively enhance resilience to climate change.

The Pilot Program for Climate Resilience (PPCR) of the Strategic Climate Fund (SCF) employs a programmatic approach to help countries around the world integrate climate resilience into development planning across sectors and stakeholder groups. With the challenges faced by Samoa in mind, as part of the PPCR, Samoa undertook a Vulnerability Assessment and Climate Resilient Road Strategy under the Enhancing the Climate Resilience of the West Coast Road (CRWCR) Project. The CRWCR Project aims to: (i) improve the climate resilience of the West Coast Road (the main road connecting the international airport to the capital Apia); and, (ii) enhance local capacity to develop a more climate resilient road network. As part of achieving the second objective, the Vulnerability Assessment and Climate Resilient Road Strategy identified and prioritized locations that require investments to improve the resilience of the national road network based on assessing asset exposure and resilience, undertaking cost-benefit analyses and incorporating social analyses.

Following the completion of the Vulnerability Assessment and Climate Resilient Road Strategy, these reports have been used by the Government of Samoa to further guide investment plans within the road sector and to optimize the allocation of available resources. In addition, the priorities identified through the assessments have been utilized in the preparation of a new climate resilient transport project.

TASK OVERVIEW

As part of the Samoa Vulnerability Assessment, the following tasks were undertaken to assess the risk of transportation network failures by identifying geographical areas at high risk of exposure to natural hazards and assets vulnerable to future climate change impacts.

Task 1 – Rainfall and climate change projections:

This task involved the production of precipitation Intensity-Duration-Frequency (IDF) curves[2] to help form the basic starting point for any future drainage designs in Samoa. A milestone for the Vulnerability Assessment was the application of updated hydrological data for Samoa as the basis for making rainfall projections. Historical daily rainfall data for two stations – Apia and Faleolo – covering 30 years (1984 – 2014), monthly data from the 1980's for four stations on Savai'i and one on Upolu, and 10-minute data from 2010-2015 for two stations – Nafanua and Afiamalu – were obtained. In addition, the reported long-term increase in relative sea level at Apia (3.7 millimeters per year since 1993) was used as an indication of sea-level rise (Australian Bureau of Meteorology). In addition, rainfall and temperature parameters were modeled as part of the climate change scenarios using the Delta Method[3].

In addressing climate change risks, the ability to address uncertainty is often questioned. There can be disagreement on the scale and direction of future changes when using global climate models, and it is not possible to predict changes in greenhouse gas emissions in the future decades. Due to the many variables involved in making projections, such as the choice of climate model and the timeframe of projection, Samoa's Vulnerability Assessment included a straightforward sensitivity analysis to assess how different projections may produce different impact results and different approaches to improving the resilience of the network. An assessment of the climate model used, Representative Concentration Pathways[4], future year and Annual Return Interval[5] were examined as part of the assessment process.

Task 2 – Vulnerability Analysis of Road Network:

This task involved:

I. *Performing geo-referenced mapping* of the critical road links, bridges and any other damageable asset. The emphasis on damageable assets here is important because the risk assessment of a road network can be simplified at times by identifying items that, using expert judgment, are much less damageable than all the others. For example, stretches of road located inland at locations not subject to landslides or flooding may be identified as less exposed to simplify the risk assessment study. If warranted, this simplification can help to make this task more manageable, and the consequences of such a simplification on the robustness of the assessment, is usually negligible. In Samoa, surveys were undertaken of the road network using a Blackvue dashcam, to give a video recording, GPS coordinates and an estimation of road roughness from

[2] A graphical representation of the probability that a given average rainfall intensity will occur.

[3] A statistical downscaling approach using historical large-scale atmospheric and local climate characteristics and global climate models to project future local climate characteristics.

[4] Four greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change.

[5] The average or expected value of the periods between exceedances of a given rainfall total accumulated over a given duration.

acceleration data. The results of the surveys were used to identify the damageable assets (e.g., road links and bridges susceptible to damage from tropical cyclones).

II. *Assessing the unit replacement cost* of any such item (for road links, it could be cost per kilometer, while for bridges it could be the replacement cost of the entire bridge).

III. *Categorizing any damageable asset belonging to the road network into vulnerability classes*, namely groups of assets that have similar vulnerability to the effects of the natural events to which they are exposed. For simplicity, if we assume that the network is comprised only of roads and bridges, existing roads could be placed into four classes, primary and secondary roads and those in "good" or in "bad" condition; and existing bridges can be categorized into types defined in terms of construction material (e.g., reinforced concrete or steel), span length, and year built brackets (e.g., before 1970, between 1970 and 2000, and after 2000).

The output of the exposure component is an 'asset register' i.e., a geo-referenced database containing all the damageable components of the network (e.g., road links and bridges) divided into appropriate vulnerability classes, their replacement cost and, in the case of networks, the connectivity of all the components within the network. The existing asset register in Samoa is the Samoa Asset Management System (SAMS) a computerized system developed to help strengthen institutional capacity to proactively manage assets, which is managed by the Land Transport Authority (LTA). Outputs from the Vulnerability Assessment (e.g. results from the Blackvue recordings) are being used to strengthen SAMS.

Task 3 – Natural Hazard and Climate Change Risk Assessment:

This task involves:

I. *Deciding the types of natural events* that the risk assessment study intends to consider and selecting the effects of the natural events that one intends to consider in the risk assessment of the assets at hand. For road networks in PICs an obvious choice would be tropical cyclones (with associated storm surge risk) and earthquakes (with associated ground shaking and earthquake-induced tsunami risks). Note that the type of assets exposed drives this selection. Three main groups of hazard were identified in Upolu and Savai'i: (i) storm surge and coastal inundation; (ii) landslides; and, (iii) river and tributary flooding. The probability of occurrence were then classified as high, medium and low. Coastal hazards for example were delineated based on proximity of the road to the coastline: High (<5 meters); Medium (5-50 meters); and, Low (>50 meters). Hazard indicators were chosen associated with road damage and loss of accessibility and connectivity. The approach to addressing vulnerability (the degree of exposure and resilience) in Samoa was time-bound to prioritize actions, with high vulnerability addressed in the short-term, medium vulnerability in the medium-term and low vulnerability in the long-term.

II. *Estimating the likelihood of occurrence* of the natural events of different "strength" (for strength we mean the potential for the hazard to generate different levels of impact) that may pose a threat to the road network. This task, which is empirically based, requires a statistical analysis of the historical catalogues of events in the region and any modern technology that can provide useful information. This task is very time consuming and may require multi-disciplinary expertise including that of meteorologists, climatologists, seismologists, geologists, geophysicists and engineers. In the case of earthquakes, this task assumes that in historical and recent pre-historical times the occurrence of earthquakes can be considered a stationary process. Therefore, the rates and the characteristics of earthquakes that will occur in the future can be estimated from the rates and the characteristics of earthquakes that have occurred in the past. For the case of tropical cyclones, however, this task is made more complex by the effects of climate change as the occurrence and characteristics of future cyclonic events may not be the same as those that occurred in the past.

III. *Predicting the severity of the effects of any natural event* of given characteristics. This task entails, for example, the ability to estimate the amount of storm surge inundation caused by a tropical cyclone, and requires the specific modeling skills of oceanographers, meteorologists, and earth scientists.

The use of scenario analysis here in subtasks *I* and *II* provide a means to help strategically manage assets and planned investments by anticipating trends and developing alternative pathways, thereby moving assessments towards being more forward looking. Scenario analyses have emerged as an important tool to help inform strategic decision-making processes in the face of uncertainty. Storm surge inundation modeling was undertaken to determine the impacts of tropical cyclones on the road network in Upolu and Savai'i, and is provided in further detail below.

A Robust and Implementable Approach to Hazard Assessments: Storm Surge and Inundation Modeling

Increases in heavy rainfall, strong winds, storm surges, and high sea levels are predicted for Samoa (Pacific-Australia Climate Change Science and Adaptation Planning Program, 2014), which will have detrimental consequences for the Samoan Road Network and transport sector assets. Hazard assessments can be complex, expensive and onerous, and are often not feasible for PICs. To assess the risks to Samoa's road network, a practicable approach was undertaken at an appropriate scale based on data that was available and accessible.

To assess the impacts of tropical cyclones on the road network and to assess the impact of loss of connectivity and access in priority areas, storm surge modeling was undertaken using the experience of recent severe weather events including Tropical Cyclone Evan (2012), Val (1991) and Evan (1997). Five study sites across Upolu and Savai'i were chosen for the simulation of coastal inundation (Figure 1).

Figure 1. Inundation map showing maximum surface elevation on Upolu (East), following cyclone Evan. The red line indicates the main coastal route (Source: Government of Samoa, 2017b).

The analysis included three main undertakings:

1. **Data collation and review:** relevant data and previous reports were collated and reviewed to provide a full understanding of the issues. In addition, bathymetric and topographic data was gathered from a remote sensing method known as Light Detection and Ranging (LiDAR) and was incorporated into the analysis as well as the production of a digital elevation model.
2. **Cyclone wind analysis:** significant historical tropical cyclone events were selected.
3. **Numerical modeling:** MIKE 21 Flexible Mesh modeling suite was used to set up a regional scale coupled hydrodynamic and spectral waves model covering Upolu and Savai'i and encompassing the approach path for the selected cyclones.

The output of the analysis was a calibrated hydrodynamic model coupled with a spectral wave model for wind waves. The impact of storm surge on the road network was assessed and the roads with the highest inundation depths were identified as most vulnerable to help prioritize sites selected in the Climate Resilient Road Strategy.

Task 4 – Assessment of Vulnerability:

I. Vulnerability assessments require the ability to estimate the level of damage, and therefore downtime and monetary loss that would be required for fixing the damage suffered by any asset in the vulnerability classes identified (e.g., a primary road link in good condition) when it experiences any given level of intensity of the effects under consideration (e.g., an inundation of 2 meter of storm surge water for 24 hours).

II. Considering the damage estimated for all the damageable components of the network, for any given earthquake or tropical cyclone, the model needs to estimate the level of damage of the entire network measured in terms of the selected metric (e.g., network service disruption and losses). For example, if the model predicts that after a storm several road links have minor damage but are passable, some links have severe damage and are not passable, and a bridge has collapsed, what is the downtime of the entire network before the damaged items are temporarily fixed and the traffic can resume? What are the direct repair losses and the indirect losses to the stakeholders due to the road network damage?

III. A large focus in assessing network vulnerability has been on technical adaptation and the economic costs of associated with ensuring the ability of a road network to maintain its level or performance following an event, and therefore often solely limited to indicators of reliability. As part of the Samoa Vulnerability Assessment, aspects of social vulnerability were investigated and linked to the engineering and economic analysis to provide a more holistic approach to assessing the costs for adapting to climate change. Three indicators were used including: (i) quantifiable social indicators such as age, income, gender, employment, health and disability; (ii) relevant quantifiable infrastructure and facilities such as availability and accessibility of escape paths, sirens, wheelchairs for persons with disabilities; and, (iii) qualifiable indicators such as the existence of a community disaster management plan (community preparedness), reliance on the road to access emergency services and/or escape (distance to nearest hospital and safe house), and knowledge of climate change.

IV. A cost-benefit analysis assessment was undertaken to inform an investment plan. The economic indicators – beneficiaries, costs, internal rate of return and net present value (NPV) – were used to assess the comparative performance of a variety of alternative options for investment. Depending on the risk-aversion of decision makers, several criteria can be used to choose the best alternative. Very risk-averse decision makers can choose the alternative that minimizes the maximum regret over all scenarios considered. In other words, this is the alternative whose expected NPV of the losses (direct plus indirect costs) over the chosen period is minimum under the worst-case scenario. Other decision-makers might choose the alternative whose expected NPV of the losses (direct plus indirect costs) over the chosen period is minimum in as many scenarios as possible. Others might choose the alternative whose expected NPV of the losses (direct plus indirect costs) over the chosen period is minimum on average over all scenarios. In any case, the decision makers will need to keep in mind the possible consequences of their choices in the worst-case scenario, and be ready to react in case it materializes.

The output of this task consists of multiple sets of so-called damage functions and downtime functions for all asset classes. Damage and downtime functions are probabilistic relationships that provide expected level of losses (e.g., 10 percent, 20 percent, etc.) or of repair time (and their uncertainty) for any given level of intensity of the effects of an event (i.e., tsunami wave heights caused by earthquakes). Damage functions are used to estimate the direct ground up losses (as a fraction of the replacement cost of the asset) suffered by any component in each vulnerability class present in the network, while downtime functions are used to estimate the time needed to fix the damage and make the asset operable again. The total direct losses caused by an event are simply the sum of the losses suffered by each component. The computation of network downtime is, however, less immediate and it is specific to each network. For any pattern of damage to the components of the network and related downtime, the length of the service disruption of the network (if any) can be estimated with only that knowledge and the knowledge of the connectivity of each component.

Task 5 - Probabilistic Risk Assessment:

The inclusion of catastrophe risk assessments, which incorporate probabilistic risk analysis, provides one option to improving the vulnerability assessment methodology. Since there are many sources of uncertainty when it comes to predicting the impacts of catastrophes, the additional inclusion of probabilistic methods can help the decision-making process in the face of uncertainty. The output of catastrophe risk assessments is a stochastic[6] catalogue of simulated future events to each component of the road network. The benefit of this method is that it combines multiple modeling views of exposure, hazard and vulnerability to obtain various alternative views of risk, providing the most comprehensive set of information for the decision-making process. The Samoa Vulnerability Assessment did not include a catastrophe risk assessment, and though the addition would have been a valuable addition to bring further confidence to the analytical underpinnings of the risk piece, the feasibility of this approach in low capacity environments where data challenges (both in terms of availability and accessibility) are a binding constraint requires deliberation. To address this challenge in Samoa, the consultants' approach to the storm surge inundation modeling by assessing the impact of three relatively recent cyclones across priority sites provided a practical and replicable approach valued by the client. In comparison, Annex 1 provides a framework for catastrophe risk assessments that could be utilized in countries with higher capacity and where greater resources are available.

CLIMATE RESILIENT ROAD STRATEGY

Samoa's Vulnerability Assessment was used to inform its Climate Resilient Road Strategy, which guides the time-bound strategic considerations (short, medium and long-term) to be addressed by the Government and its line ministries. For example, coastal inundation measures can be implemented in the short to medium-term through raising the elevation and coastal protection works, while a long-term solution may be an alternative inland route. Thus, a road strategy report may outline a general climate change adaptation policy framework and objectives, recommend a program of priority investments and other interventions at specific risk locations, and propose specific policy reforms required to provide a foundation for climate change adaptation and to address natural hazard vulnerability in the sector. As previously noted, to address the vulnerabilities identified, high vulnerabilities may be addressed within the short-term, medium in the medium-term and low in the long-term. Examples of the short, medium and longer-term priority investments identified in Samoa include: retrofitting and rehabilitation of existing infrastructure, securing alternative inland routes, improved

[6] Randomly determined or having a random probability distribution.

maintenance regimes (routine, preventative, remedial), and capacity development (Government of Samoa, 2017a).

It is important to note here that documents should link to the existing institutional and policy framework to further embed climate change considerations into road infrastructure development and to help speed up the process at which actions can be undertaken. As such, Samoa undertook a review of existing plans and strategies to ensure that any recommendations from the outputs also aligned with national and regional aspirations. The Vulnerability Assessment and Climate Resilient Road Strategy have therefore been framed within the existing institutional context.

Lastly, an area within the network that is considered less vulnerable today will have a different vulnerability in the future should its infrastructure or population change. Therefore, systems planning needs to be treated as a dynamic process, which means tools such as Samoa's Vulnerability Assessment and Climate Resilient Road Strategy need to be updated regularly to provide policymakers with the best available information so they can continue to make informed investment and policy decisions.

OUTCOMES

The approach undertaken in Samoa through its Vulnerability Assessment helped to:

- Provide a general climate change adaptation policy framework and objectives for the national road network;
- Identify and prioritize specific locations that require investments to improve the resilience of the road network including short (1-5 years), medium (5-10 years) and long-term (10+ years) resilient investments;
- Provide an outline of specific measures to update design and planning standards, and maintenance procedures considering expected climate change;
- Develop and strengthen tools to assess the vulnerability of road assets to climate change events, including the methodologies for determining the adequacy of existing roads to resist climate change impacts; and,
- Review the institutional and legal framework and recommendations for specific reforms required to facilitate climate change resilience within the road sector from infrastructure and operational perspectives.

This engagement has provided Samoa with an investment and maintenance strategy to enhance the climate resilience of the road network as well as new methodologies, techniques and software and the institutional capacity to more effectively plan and manage the road network. Samoa's Cabinet Development Committee approved the Vulnerability Assessment and Climate Resilient Road Strategy in August 2017, recognising the importance of the reports for inclusion within the existing institutional framework and setting a milestone of transformative change in the way that climate change is addressed in Samoa's transport sector.

LESSONS LEARNED

Through the work undertaken in Samoa, practical operational lessons were identified that should be considered when trying to undertake a similar exercise in other small island nations:

Management. The management of such a complicated assignment can be a challenge, particularly when it comes to reviewing deliverables. It is sensible to undertake capacity building during preparation and implementation of the vulnerability assessment to ensure Governments can effectively oversee these multi-disciplinary teams and then implement the recommendations derived from their work.

Maintenance. There is a general lack of regular maintenance in many PICs and this is a pressing issue that needs to be prioritized. This entails not just regular routine maintenance such as clearing drains, but also preventative maintenance such as conducting slope stabilization to prevent landslides, which can cause damage to road links and then require road clean-up (routine maintenance).

Data Availability. Robust vulnerability assessments often require copious amounts of data for rigorous analysis. However, in small island countries such as Samoa, good quality datasets are generally unavailable, often because the country has not had the resources to record the data. In other cases, the datasets may be available, but not accessible as the distribution from the owners and custodian to the project team dealing with risk assessment is not always smooth. To overcome the accessibility issue, it is important that the relevant stakeholders are well informed about the work and buy into the value it will deliver to all of Government and ultimately the people. Thus, it important to engage coordinating Ministries (i.e. the Ministry of Finance in most PICs) early in the activity, as they play a pivotal role in ensuring effective communication across relevant line Ministries and securing their participation during the data-gathering process. At the end of the assignment, all data assembled should be catalogued and provided to Government as well as stored in an open data repository for future access.

Procurement. National road network Vulnerability Assessments need to be conducted by multi-disciplinary teams with skills and experience in several areas (e.g. engineering, disaster risk management, climate change analysis, economics, hydrology, GIS mapping, environmental and social assessment, policy review). To properly assess the qualifications of such teams, the procurement evaluation committee must have the ability to assess the proposed team's skills and methods to ensure technical proposals are not over-weighted in any one area (e.g. engineering, disaster risk analysis, climate science), but adequately balance all aspects for optimal assessment. Samoa followed best practice by recruiting a technical advisor to develop a methodology and train the panel to adequately assess the various technical proposals.

Feasibility. It is however important to keep in mind that the assessment undertaken is feasible in terms of consistency with monetary and non-monetary constraints. For example, moving a coastal road from the coast to a mountainous area two kilometers inland may be outside the available budget. Alternatively, building a sea wall along a long stretch of coastal road to reduce the likelihood of coastal inundation and storm surge impacts may be economically viable but may only be a short-term solution and may have negative environmental impacts or may not be acceptable to communities in the area. The cost and the mitigated risk of feasible alternatives (e.g., road networks with different proposed variants) therefore need to be evaluated. In addition, the inclusion of complex modeling and risk assessments need to be appropriate for the context. It is also vital that the Government targets an acceptable level of reliability of road networks and, therefore, limits the likelihood of service disruption to levels that are compatible with realistic expectations of the stakeholders.

WAY FORWARD

The pilot approach undertaken in Samoa is a valuable addition to transport sector planning and provides a replicable option for other PICs that can be tailored to country needs and lessons learned. Building on lessons learned from the Samoa Vulnerability Assessment, a key discussion for PICs wanting to conduct similar national road network assessments is to determine the level of sophistication desired, considering the trade-offs between the additional benefits of including a probabilistic risk assessment and the time, resources and capacity available.

CONTRIBUTORS

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RESOURCES

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ANNEX 1 A FRAMEWORK FOR PROBABLISTIC RISK ASSESSMENTS

Task 5 – Probabilistic Risk Assessment:

The risk assessment component uses the outputs of the tasks outlined above and computes the direct losses and downtime caused *by each* earthquake or tropical cyclone in the stochastic catalogue of simulated future events to each component of the road network. Consequently, it computes whether disruption of service for the entire network is expected and, if so, for how long. If disruption of service is expected for a period (e.g. 2 months) this component will also evaluate the indirect losses to the stakeholders. The direct losses and downtime for each network component are computed by coupling the estimation of the effects of the event at each component location (e.g., a 2-meter tsunami wave at location 1, 2.5 meter at location 2, etc.,) with the damage and downtime functions tailored for the vulnerability class of each component. The absolute value of the direct losses is obtained by multiplying the damage ratio suffered by each component by its replacement value.

The computations above were explained as if they were deterministically made based on mean values. However, this is not the case in state-of-the-art models, which account for uncertainty in the predicted values of the effects for each event, and for damage or downtime given the level of the effects. As stated above, these computations are repeated for all the events in the catalogues. The likelihood of occurrence of the loss and downtime distributions computed for any event is simply equal to the annual rate of occurrence of that event that was computed. Computations for all events are recorded and assembled in such a way that the final risk profiles for the road network are obtained. The loss risk profiles can be expressed simply in terms of annual probability of exceeding losses of different amounts (e.g., US$1 million, US$2 million, etc.) caused by tropical cyclones and/or earthquakes. Similarly, for downtime, the risk profiles provide the same information for network disruption of service of different time lengths (e.g., 1 day, 2 days, 1 week, etc.). The risk profiles can be generated for the road network in the 'as-is' condition and for all the feasible network variants proposed during the decision-making process and analyzed by the cost-benefit analysis.

Note that in the definition of the risk-modeling framework above there was no mention to the scientific uncertainty that analysts necessarily have about their models for describing exposure, hazard and vulnerability. The science is mature, but the empirical data supporting these models is not plentiful. Hence, competing yet legitimate models can be proposed and they would only differ by how the limited data available has been interpreted and utilized. In large-scale, well-funded projects the uncertainty about models (called epistemic uncertainty) is accounted for using an established methodology called the *logic-tree approach*. This method that combines multiple modeling views of exposure, hazard (as done by United States Geological Survey, for instance, to develop seismic hazard for the United States of America), and vulnerability to obtain multiple alternative views of risk would provide the most comprehensive set of information for decision-making. The effort needed for such a detailed treatment, however, is often beyond the reach of many projects. When the budget does not allow for such detailed approach, it is still important to test the robustness of the solutions chosen to the assumptions made, with a sensitivity analysis along all uncertain dimensions, and to select solutions that provide acceptable performance under multiple assumptions for exposure, vulnerability and hazard distributions.

ANNEX 2 Examples of Priorities for Climate Resilience

An example of summarized actions and outcomes from the short to long-term are provided below based on the experience in Samoa.

	Short-Term	Medium-Term	Long-Term
Infrastructure	• Install protective measures e.g. sea walls • Increase road height • Improve storm water capacity • Increase bridge heights • Improve pavement standards	• Improve/stabilize slopes • Create additional cross drainage	• Roll-out of a comprehensive infrastructure upgrade plan
Design and Planning	• Relocate assets along same road • Develop alternative evacuation routes • Undertake a Vulnerability Assessment and Climate Resilient Road Strategy • Designate "dangerous roads" • Make use of basic IDF curves	• Establish and/or upgrade inland routes • Update the Vulnerability Assessment and Road Strategy	• Plan and invest around inland routes
Maintenance	• Increase maintenance frequency • Clean drains/culverts prior to cyclones • Develop community based contracting model • Strengthen asset management systems – information sharing (data/statistics)	• Conduct regular routine and preventative maintenance • Use surveys and asset management data to improve maintenance budget	• Employ a comprehensive maintenance plan and policies that are both reactive and proactive
Reform	• Review current legislation and policies – ranging from climate change, adaptation, and maintenance regimes and practices • Improved standard – Design Basis Memorandum (e.g., using IDF) • Resolve land acquisition function and conflicts • Address conflicting roles and responsibilities of line ministries in road resilience matters • Enhance cooperation between line ministries to address climate change across sectors	• Reflect alternative inland routes in the National Strategic Investment Plan • Use Vulnerability Assessment to inform coastal infrastructure management strategy and vice versa • Streamline climate change roles and responsibilities into Government	• Mainstream climate change into all applicable policies and operations

Capacity Building	• Involve relevant line ministries • Provide training during the Vulnerability Assessment on key processes and tools e.g., GIS, asset management	• Conduct follow-up training on Vulnerability Assessment and related tools • Integrate specialist technical advisors to increase ‘in-house’ knowledge	• Augment in-country ability to update Vulnerability Assessment, models, and asset management systems