Piloting the Use of Network Analysis and Decision-Making under Uncertainty in Transport Operations

Preparation and Appraisal of a Rural Roads Project
in Mozambique under Changing Flood Risk
and Other Deep Uncertainties

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Abstract

This paper presents a methodology to identify key priority areas for transport investments. The methodology uses a geospatial data-driven approach and then proposes an innovative economic analysis for project appraisal. The two main steps involve (i) prioritization of road interventions based on a set of economic, social, and risk reduction criteria; and (ii) assessment of monetized and nonmonetized costs and benefits of road interventions under many scenarios covering the uncertainty on future risks and other factors. This

methodology is used at different stages of project preparation for a rural roads lending operation to the Government of Mozambique. In the two regions of Mozambique considered, the analysis prioritizes regions along the coast when combining agriculture, fisheries, poverty, network criticality, and hazard risk criteria. With a limited budget of US\$15 million per district, the results show that investing in repairing and rehabilitating culverts and bridges is the intervention that performs better under most of the scenarios.

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PREPARATION AND APPRAISAL OF A RURAL ROADS PROJECT IN MOZAMBIQUE UNDER CHANGING FLOOD RISK AND OTHER DEEP UNCERTAINTIES

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Introduction

Many of the poorest countries in the world depend heavily on the agriculture sector. In Mozambique, for example, agriculture sector employs about 70 percent of the workforce and generates about 25 percent of its GDP (E. Baez and Olinto 2016). However, the agriculture production is low in comparison with neighboring Sub-Saharan Africa countries due to low market-oriented farming, limited use of agricultural technology, and poor rural access, among others (The World Bank 2017). In fact, as stated by the International Fund for Agriculture Development, providing reliable connectivity to farmers is key for achieving sustainable growth (IFAD 2016). In the Zambezia and Nampula provinces, the poorest provinces in Mozambique, rural accessibility is very low and most farmers practice subsistence agriculture (Iimi et al. 2016). Improving farmers' connectivity to markets, through transport investments, would increase their revenues and reduce poverty, while also improving the national economy (by reducing food import needs for instance) (Bell and van Dillen 2012).

But the benefits of transport investments also depend on transport reliability under extreme and unexpected events (Cervegini et al 2016). Mozambique is affected by river floods and storm surges that repeatedly damage the transport infrastructure and create disruptions in the road network (World Bank 2016). Since the Mozambican road network has a low redundancy, those disruptions sometimes isolate communities for months, and thus have a significant detrimental impact on their local economics. Incorporating components of climate adaptation and natural hazard risk reduction in transport investments is therefore critical to ensure transport reliability, particularly in areas with low road redundancy and high exposure to climate events.

Additionally, in a budget-constrained scenario, and with many roads in need of rehabilitation or repair, it is important to prioritize the rural road interventions that will trigger the highest socio-economic benefits, and ensure the reliability of the transport network under disruptive weather events.

This paper addresses the challenges raised above and proposes a method to: (i) identify critical and vulnerable roads, and (ii) assist decision-makers on the selection of interventions which can ensure the reliability of the road network for rural communities. The methodology is applied to a feeder roads project in two provinces in Mozambique: Nampula and Zambezia. The paper is divided in two sections.

The first section defines the methodology to identify critical and vulnerable roads. In this section, we analyze the criticality of the roads, based on metrics of network performance and socio-economic attributes. Then, we assess the exposure and the vulnerability of the road network to river floods and storm surges and calculate disruption risk in each district under multiple future scenarios. Finally, we combine criticality and risk to identify which districts should be a priority for investment. The methodology is applied to Zambezia and Nampula provinces in northern Mozambique with the goal of selecting the top three districts in each province. The method proposed in this first section supports investments prioritization in a quantitative and transparent manner.

In the second section, we present the method to select climate resilience interventions. We begin by identifying several sets of investments based on stakeholder consultations in each of the districts selected in the previous section. We then assess the robustness of those road interventions using a cost-benefit analysis under thousands of possible future scenarios. The benefits include risk reduction expressed in terms of reduced expected damage to the infrastructure and reduced expected user losses due to road disruptions. This method can be used for the economic analysis of transport projects required during project appraisal. The paper ends with a discussion on the benefits of using this method in World Bank operations in transport project and other infrastructure investment.

Background

Roads, bridges and culverts are the most vulnerable elements of a transport system to adverse weather conditions (EEA 2014; Nemry and Demirel 2012; NRC 2008). Disruption of those elements may have severe cascading reactions along the entire transport system, isolating rural villages or towns and disrupting trade or business operations (Koetse and Rietveld 2009). Climate change is exacerbating these risks, increasing the frequency of disruptions along the transport systems, and is challenging every single step of the transport planning process. Transport infrastructure has become one of the most vulnerable sectors to climate change in the civil infrastructure realm (Bollinger et al. 2014; Meyer et al. 2010).

The frequency and magnitude of future floods, storms and other extreme weather events fostered by climate change pose challenges to transport engineering design, maintenance, rehabilitation scheduling, and disaster preparedness plans. The current design standards, practices and building codes have become obsolete as they were developed based on historical weather patterns (Lisø 2006). Failing to update standards, practices and codes for new and existing transport projects will lead to an increase of maintenance, repair and rehabilitation budgets in almost every road administration agency around the world (Espinete et al. 2016, Schweikert et al. 2014), all contributing to negative impacts on transport users (Bruin et al. 2009; Hambly et al. 2013; Keener 2013; McBeath 2003).

In response to these recognized threats to transport infrastructure, many professionals and stakeholders in the transport field are moving to incorporate climate change considerations into transport planning, engineering and design (Ebinger and Vandycke 2015, Henning et al 2017). This approach aims at lowering infrastructure degradation rates, life-cycle costs and negative social impacts, creating a more sustainable transport asset management system and overall increasing the resilience of the transport system to natural disasters (EEA 2014; Meyer et al. 2010; Meyer and Weigel 2011).

As part of a sustainable transport asset management system, a network-level approach is required to fully capture the vulnerability of the transport system and to evaluate the real impact of the disruption (Berdica 2002; D’este and Taylor 2003). When a bridge is disrupted due to extreme floods, users will use an alternative route to reach their original destination. If that alternative route leads to a much longer travel time, or if there is no alternative route available, the disruption cost can be very high. Network-level analyses allow identifying the most vulnerable segments (in terms of highest lack of redundancy) and test the resilience of the overall transport network (Knoop et al 2012; Jenelius et al. 2015).

A complex challenge that arises while quantifying both the project-level impact and the network-level impact of future weather events is the uncertainty associated with climate change projections (Dessai et al. 2007; Hallegatte 2009). In fact, climate change is an example of “deep uncertainty” (Fankhauser et al. 1999; Jones 2000; Lempert et al. 2004; Yohe and Neumann 1997). Deep uncertainty arises when decision-makers cannot agree on (i) the models to describe the system, (ii) the probabilities and interdependencies of the inputs of the model and (iii) how to measure the desirability of the model outcomes (Lempert et al. 2004). This deep uncertainty adds complexity to the prioritization process of interventions, and can lead to poor decisions in a traditional deterministic cost-benefit approach (Fankhauser and Soare 2013; Pittcock et al. 2001).

Pushed by the need to effectively prioritize infrastructure projects under climate change, researchers have been developing a set of new methods and techniques to support decision-makers under situations of deep uncertainty (Hallegatte et al. 2012). All these techniques fall under the umbrella of *Decision-Making under Deep Uncertainty* (DMDU or sometimes simply DMU). These methods have been applied to different types of infrastructure projects but mostly are used in the water management context. There are still very few

examples of DMDU applied to transport infrastructure projects even though transport planning is facing most of the same challenges and issues.

This paper builds upon these two concepts; network-level analysis and decision-making under deep uncertainty techniques. It presents the integration of these two concepts into a prioritization study (in section I) and economic analysis (in section II) of different road interventions in rural Mozambique. The methodology presented in this paper captures network-level climate adaptation co-benefits in the cost-benefit analysis. Additionally, the methodology presents an approach, grounded in a robust decision-making framework, that properly deals with the large range of plausible future scenarios in which the investments will operate.

Section I: Prioritization of roads and districts

The goal of this first section is to present a comprehensive methodology for prioritization of districts for roads interventions based on geospatial data, network analysis and risk assessment. The prioritization is based on two pillars; (i) socio-economic criticality and (ii) current and future hazard risk to the roads. Socio-economic criticality is a composite indicator based on (1) lack of network redundancy, (2) proximity to potential agriculture clusters, (3) proximity to potential fishery clusters, (4) current agriculture production and (5) poverty rate in the district. The second pillar, hazard risk, is calculated using flood maps, for current floods and under climate change scenarios, and damage functions for the different pieces of infrastructure in the road system. The hazard risk is calculated as expected annual damage to the infrastructure using 10 return periods, in four climate scenarios (current climate, low, medium and high climate change).

The following sections describe in detail each of the two pillars and its components and present the results for two provinces in central and northern Mozambique; Zambezia and Nampula.

Methodology

Criticality

To help decision makers prioritize investment in Mozambique, we identified the most critical links in the road network. Here we define the criticality of a link as the loss of network performance if this link is removed from the network (Rozenberg et al. 2017). The metrics for evaluating the performance are:

- Cumulated Road user cost or RUC, defined as \$-vehicle and based on road condition (IRI) and data from the HDM4 model
- Total kilometers traveled
- Total travel time, based on average speed from HDM4 based on road condition (IRI) (we assumed free flow speed in all the network – traffic congestion was not considered as traffic volumes are very low in the study area, under 2,000 AADT).

We first calculate these three variables in a baseline with the complete existing network. We then remove each of the links one by one and we recalculate the performance of the network with respect to these three indicators based on the assumption that travelers will take the secondary best route when the optimal route is disrupted (see Figure 1 for an example of the approach). The optimal and second best routes are the routes that minimize the total road user cost between the origin and destination. The additional cost, time and length of travel due to the disruption of a link are aggregated over all Origin-Destination pairs and assigned to the disrupted link to determine its criticality.

Figure 1: Example of link disruption and redundancy analysis

The lack of redundancy is only one way of measuring the criticality of a link, and other attributes may be relevant for the decision-makers. In the current study, proximity to poverty hotspots, current agriculture production and fishery or agriculture potential are particularly important for determining where to intervene in the network. We thus create five categories of criticality for each of these attributes (see the annex for individual maps), combine them using equal weights and produce a new criticality map. The assumption of equal weight between criticality attributes could be altered to answer certain priorities of the decision-maker. For instance, for a decision-maker who aims to invest in roads to promote fishery, we could give a higher weight to that attribute.

The criticality values at the road level are then aggregated at the district-level. The new criticality index is now used to rank districts within one province. To aggregate criticality at the district level, we sum criticality indices weighted by the length of the roads.

Exposure

The second step of the analysis is to identify the exposure of the network links to climate events. We focus our analysis on flood risk and we combine flood coming from riverine and storm surge. The annex describes the modeling that was done to produce water depth maps for current, climate change and land use change conditions for 10 different flood recurrence intervals (from 5 to 1,000 years).

Vulnerability

The next step of the analysis is to calculate the vulnerability of the road infrastructure to different water levels. This vulnerability is expressed as the cost of repairing or rebuilding bridges, culverts and road surface when a flood occurs.

The bridges inventory used comes directly from the ANE GIS database and uses the conditions surveyed in 2015. There is actually no inventory for culverts. However, we found the need of including culverts in the analysis as they can easily be damaged by flood and disrupt the road. In order to estimate the location of culverts, the river map was intersected with the road network. The intersection points that were not included in the bridge inventory were assumed to be culverts. The estimation has been calibrated with data

collected on the field for some roads. Our estimation seems to be very conservative and a larger number of culverts is more realistic.

For bridges and culverts, the damage is modeled as a % of total replacement cost based on the difference between the observed water level and the water level the structure was designed for. The following simplistic damage equation is used:

$$D_i = \left(\frac{WL_{cc_i} - WL_d * Dc}{WL_d} \right) * 1/Cr * Rc \quad (1)$$

- WL_d = water level design comes from the design standard of 20 yr for culverts and 100 yrs for bridges on primary and secondary roads (probability is based on past events)
- WL_{cc_i} = water level for climate change projection for return period i
- Dc = drainage capacity rate
- Cr = condition rate
- Rc = replacement cost

We add two factors, drainage capacity rate (dc) and condition rate to be applied to the damage. Drainage capacity rate is set at 0.7 (as default), and it reduces the total amount of water that the structure can actually drain. Condition rate is applied directly to the damage as a multiplying factor, to account for the fact that structures in poor condition will incur more damage than structures in excellent condition. The condition rates are set to 0.7, 0.5 and 0.3 for good, fair and poor condition.

The damage cost on road surface is based on 3 thresholds; 0.2, 0.5 and 1.5 meters of water above surface. It is assumed that roads are built at ground level (no embankments). For each of the three water level thresholds we assigned a % of total replacement cost if surpassed, different for paved or unpaved: [1, 2, 20%] for paved and [20,50,100%] for unpaved.

Risk to the infrastructure (Expected Annual Damage to the infrastructure)

The final step is to combine the hazards, vulnerability and exposure to estimate the flood risk that each district faces annually, expressed in terms of damage to the infrastructure.

Damages are calculated for flood events with 10 different intensities (5, 10, 20, 50, 75, 100, 200, 250, 500, 1,000 return period), and for four different climate scenarios (one based on past climate and 3 climate change projections), in each of the river basins in the two provinces. Individual events are then aggregated, for each climate scenario, into expected annual losses (EAD). To calculate the EAD the trapezoidal rule was used, using the losses associated to each event and its probability of occurrence as the inverse of the return period.

$$EAD = \frac{1}{2} \sum_{i=1}^n \left(\frac{1}{T_i} - \frac{1}{T_{i+1}} \right) (D_i + D_{i+1}) \quad (2)$$

Where i is an integer between 1 and 10, T_i is the i^{th} return period, and D_i is the damage to the infrastructure corresponding to T_i .

For the prioritization process we use only the risk expressed in terms of damage to the infrastructure and we do not calculate the risk for users. The risk in terms of user costs will be used for assessing the benefits of interventions. This is because the risk in terms of damage to the infrastructure can easily be calculated at the link level and then aggregated at the district level, while the risk to users has to be calculated at the country level – since trips crossing the flooded area can come from all over the country – and is not relevant at the district level.

Prioritization

The prioritization is a combination of the criticality identified before and the risk to the infrastructure. A prioritization matrix is built to combine criticality and risk, and displayed below in Table 1, giving a 1 to a very low risk road and a 5 to a very high risk road. For example, a district identified as low priority will have a low risk, and will be low priority for investment, no matter the level of risk. On the other side of the spectrum a road identified as highly critical will range from medium to very high priority and therefore will be a priority for investment, as any disruption will cause a huge burden for users and the local economy.

Table 1: Risk Matrix

		Risk to the infrastructure				
		1	2	3	4	5
Criticality	1	1	1	1	1	2
	2	1	2	2	2	3
	3	2	2	3	3	4
	4	3	3	4	4	5
	5	3	4	4	5	5

Results: Zambezia and Nampula

Baseline Network Model

We first selected the nodes and roads of Mozambique's network that were useful for the analysis. Even if we focused on Nampula and Zambezia, we modeled the national network since trips from and to those provinces have origins and destinations in the entire country. The road national administration (ANE) provided the classified road network, and we completed it with an assessment of the conditions of unclassified roads in the provinces of Nampula and Zambezia using an innovative smartphone-based technique (Wang and Guo 2016, Espinet et al. 2017). This last set of roads was merged into the classified roads to obtain a complete transport network. The clean new network is composed of 798 links containing paved and unpaved roads, and primary, secondary, tertiary and unclassified roads (Figure 2).

We identified, in consultation with local authorities, 138 major Origin/Destination nodes including major population clusters, seaports, airports, border crossings and, of special interest for this study, agriculture production clusters in the provinces of Nampula and Zambezia (see Figure 16 in the annex). The agriculture clusters were identified based on the results from an agriculture production potential model, SPAM, developed by the International Food Policy Research Institute (IFPRI). The underlying data can be found in the annex.

The road network contains information on the traffic volume – provided by ANE and collected in the field for unclassified roads – and is shown in Figure 17 using annual average daily traffic (AADT). Using the measured traffic volumes and a simplified travel demand model, we estimated the traffic between each OD pair (see detailed methodology in the annex). A few roads – 275 km - were left out of the analysis as they did not give access to any of the identified nodes (a map highlighting these roads can be found in the annex).

Figure 2: Road Map of Nampula and Zambezia provinces

Criticality

This criticality analysis ranks most sections of the National Highway 1 (NH1) as highly or very highly critical because secondary routes are in much worse condition and cost much more to the road users (Figure 3, left panel). Some secondary and tertiary roads in the districts of Gurue, Milange and Namarroi in the north-western part of Zambezi are also identified as highly critical; the density of road in that area is low and therefore the disruption of some of those links will lead to a large detour of more than 30 USD/vehicle. Those districts are of special interest as they give access to one of the main agriculture production clusters.

Figure 3: Criticality map for Nampula and Zambezia based on RUC increase (in usd/vehicle) (left), and criticality as aggregation of redundancy, poverty, current agriculture and agriculture or fishery potential (right).

When poverty, current agriculture, and agriculture or fishery potential are combined with the lack of redundancy in the network, some other districts are identified as critical. Specifically, two districts in the south of Nampula – Angoche and Moma – are found to be highly critical due to both a very high poverty rate and fishery production proximity (see Figure 20 and Figure 21 in the annex). While poverty is more critical in Zambezia and some parts in the south of Nampula, when incorporating fishery, several roads appear to be critical in the coastal districts in Nampula. In Zambezia, a few more districts in the south appear to be critical in particular Maganja, Mocuba and Mopeia.

If primary roads are excluded from the analysis, the top critical districts in Zambezia are Maganja, Pebana and Morrumala. For Nampula, Nampula district, Memba, Namapa, Moma and Monapo are the most critical districts (see Figure 4).

Figure 4 Criticality map at a district level for Zambezia (left) and Nampula (right) without primary roads

Exposure

We overlay the road network with the different flood maps and represent in Figure 6 the water depth that each link is exposed to for a 1 in 100 flood event under past climate conditions. From the projected flood maps in Zambezia and Nampula (Figure 5) we can identify a particularly highly exposed area in the south of Zambezia that coincides with the delta of the Zambezi River.

Figure 5: Flood maps - water depth in meters - for 1 in 5 event (left) and 1 in 100 (right) for Nampula and Zambezia

Roads around the Zambezi River around the border between Tete, Sofala and Zambezia provinces are highly exposed to 1 in 100 flood events with water depths higher than 2 meters. These high depths affect some of the agriculture clusters in some parts of Zambezia Provinces, particularly those on the Zambezi and Licungo River basins. On the other side, most roads in Nampula have a medium or low exposure with maximum water depth under 1 meter, with the exception of a few roads in the northern part of Nampula in the Lurio River basin (Figure 6).

Figure 6: Exposure map for Nampula and Zambezia's road network based on maximum water depths

Vulnerability & Risk

The expected annual damage to the infrastructure was thus calculated for each road and summed again at the district level. Figure 7 shows the risk for the infrastructure in millions of US dollars for each district, excluding losses from the primary roads (the same maps including the primary roads can be found in the annex). Following the exposure results, the most vulnerable districts in Nampula are Moma, Memba and Namapa. The first one is located in the delta of the Molocue River and Namapa and Memba are in the Lurio River basin. In Zambezia, additionally to the districts in the Zambezia and Licungo Rivers, the districts of Ile, Maganja and Pebane are identified as highly vulnerable with more than US\$1 million of expected annual losses. Those three districts have a lot of smaller tributary rivers and that combined with the poor condition of the road network make those districts very vulnerable to flood events.

Figure 7 District risk for Zambezia (left) and Nampula (right) expressed as expected annual damage to the infrastructure under current climate condition, excluding primary roads

Prioritization

Figure 8 is the prioritization maps produced using the risk for the infrastructure (due to current climate) and the criticality (as a combination of redundancy, current agriculture, agriculture or fishery potential and poverty). The individual road values are again aggregated at the district level. These maps exclude values from primary roads (the same map including primary can be found in the annex). The top priority districts

in Zambezia are Morrumbala and Maganja. The top priority districts in Nampula are Moma, Memba and Namapa.

Figure 8 Risk map for Zambezia (left) and Nampula (right) at district level excluding primary roads

The objective of this first part was to identify the districts in Zambezia and Nampula where investment needed to be prioritized. The next part of this study identifies the most robust road interventions on those high priority areas with the goal of improving access and increasing resilience.

Section II: Cost-Benefit Analysis under deep uncertainties

In this second section, we present a methodology to calculate the costs and benefits of road interventions under deep uncertainty, using a robust decision-making framework (Lempert et al. 2006). The methodology is tested on five different investment scenarios in each of the districts selected above. The investment scenarios were defined based on discussions with local stakeholders during two workshops held in January 2017 in Quelimane and Nampula. Each investment scenario was constrained to a total of approximately US\$15 million. Each investment was a combination of five engineering solutions that would lead to four kinds of cost savings: reduction of flood risk for the users, repair and rehabilitation costs, maintenance expenditure and daily road user costs. The results are presented in detail for the district of Murrumbala in Zambezia to illustrate the method. A summary of the results for the other 5 districts is presented at the end of this section.

Methodology

The road interventions that are being analyzed in this study aim to improve farmers' access to markets and adapt the road network to climate change. The main impact of climate change on the roads is through riverine flood events combined with sea level rise. For that reason, the cost-benefit analysis includes flood risk reduction as a benefit in the selection of interventions. To assess this benefit, we first estimate flood risk in a baseline scenario with no intervention.

Definition of a baseline

In the baseline, it is assumed that no intervention is made, and the existing infrastructure is maintained with a low standard of routine and periodic maintenance – allowing IRI up to 16 for gravel and 18 for earth. That translates to yearly routine maintenance and periodic maintenance every 8 years (for earth roads) – these are average values based on interviews with local authorities. The existing bridges and culverts, including the ones destroyed by floods, are not rehabilitated nor reconstructed.

Traffic is expected to grow because of economic growth, at a rate of 3% per year. However, this rate is highly uncertain, and we vary this assumption later. The correlation between IRI and road user cost can be found in the annex and was obtained through the HDM4 calibrated for Mozambique (Iimi 2016). We have assumed that all traffic falls under the category of light trucks (based on discussion with locals and visual assessment).

The road network is exposed and vulnerable to floods, and we can estimate flood risk as the expected annual losses caused by floods. The probability distribution of flood events varies with climate change; thus, flood risk has to be estimated in multiple climate change scenarios.

Expected annual losses (EAL) have two components: the cost of repairing or rebuilding the damaged infrastructure (D) and the increased road user cost that users in a district must pay when they are forced to make a detour due to flood disruptions (U). In the results section the two components are shown in separate graphs, the first one labeled as 'avoided damage' and the second one as 'reduced flood risk'.

To calculate these user losses, it is assumed that the roads and bridges are impassable when the water level on the road ($WL_{cc_i} - WL_d * D_c$) is higher than 0.5 meter. Each drainage structure has a certain level of water that it can drain before water starts to accumulate on the surface of the road. Here, multiple links can be disrupted at the same time (unlike in the criticality analysis) since we simulate flood events. This means that the secondary best route identified previously may be disrupted as well. In this case user losses are associated with the use of a third best route, or fourth best, etc. In some cases, no route is available between

two nodes. We are thus unable to calculate an increase in road user cost, but we calculate the number of isolated trips as an additional decision metric.

The rerouting is assumed to happen until the original route is reopened to traffic. Therefore, repair time is a major driver of user losses.

User losses are calculated for 10 different flood events (5, 10, 20, 50, 75, 100, 200, 250, 500, 1,000 return period), and for 4 different climate scenarios (one based on past climate and 3 climate change projections), in each of the river basins in the two provinces. So, it is assumed that for a given flood event all the roads in the same basin are exposed to the flood simultaneously. Individual events are then aggregated, for each climate scenario and in each basin, into expected annual user losses (EAUL). To calculate the EAUL the trapezoidal rule was used, using the losses associated to each event and its probability of occurrence as the inverse of the return period.

$$EAUL = \frac{1}{2} \sum_{i=1}^n \left(\frac{1}{T_i} - \frac{1}{T_{i+1}} \right) (U_i + U_{i+1}) \quad (3)$$

Where i is an integer between 1 and 10, T_i is the i^{th} return period, and U_i is the increased user cost corresponding to T_i . U_i is defined as:

$$U_i = r_i * \sum_{OD \text{ pairs}} (RUC_{OD,i} - RUC_{OD,no \text{ disruption}}) * t_{OD} \quad (4)$$

Where $RUC_{OD,i}$ is the road user cost for the OD pair under flood i , $RUC_{OD,no \text{ disruption}}$ is the road user cost for the same OD pair in the absence of disruption, r_i is the repair time after flood i , and t_{OD} is traffic on this OD pair.

The repair time depends on the severity of the flood but also on the capacity of the local road agency. We thus treat this parameter as an uncertainty in the next steps.

Total expected annual losses (EAL) are the sum of the EAD (Equation 2) and the EAUL (Equation 3).

Impacts of Road Interventions – Costs and Benefits

Following consultations with local authorities, we assessed the economic performance of five different road interventions:

- Upgrade to surface treatment
- Upgrade to gravel road
- Rehabilitation of earth roads
- Clean and repair bridges
- Replace culverts

These five interventions have four kinds of benefits: reduction of flood risk for the users, reduction of flood risk for the road agency (lower repair and construction costs after flood events), reduction of road user costs due to improvement of road conditions and reduction of maintenance expenditure due to improvement of road conditions.

The reduction of flood risk for users is calculated as the difference between EAUL in the baseline scenario and EAUL with the intervention (using Equations 3 and 4). Some interventions prevent disruptions or allow a faster restoration of service; thus, the risk is lower. Also, if secondary roads are improved, even if the first-best road is disrupted, the detour can be less costly.

The decrease in flood risk for the road agency is calculated as the difference between EAD in the baseline scenario and EAD with the intervention (using Equations 1 and 2). Following interventions, the repair and rehabilitation cost (after floods) will be reduced, as damage will be lower or avoided in some cases.

With some of the interventions, a major intervention on the road surface is assumed to take place. As the condition of the surface improves, the road user cost is reduced independently from flood events. The benefits will be incurred by the road users daily and will depend on traffic. This benefit is calculated as traffic multiplied by the difference between RUC (aggregated over all OD pairs) between the baseline and intervention scenario, in the absence of floods. Similarly, because of a major intervention on the road surface the routine maintenance expenditure will be reduced giving additional annual benefits to the road agency (the maintenance savings are detailed in the annex and are obtained from RNET model).

Finally, a recent study by the World Bank finds a correlation between reduction of transport cost and increase of agriculture production in Mozambique (Iimi, forthcoming). The agriculture production is found to increase by 2.7% for a reduction of 10% in transport costs. This study is used to calculate the increase in agriculture production following a decrease in road user costs. In addition, we assume that traffic growth increases by 1 percentage points when agriculture production increases by 1%. There is a lot of uncertainty in this elasticity, so we used a range of elasticity from 0.5 to 1.5. The traffic increase is defined with the following equation and is based on the above-mentioned assumptions, where Tr_y^i is traffic volume in year y , tg is national traffic increase, ϵ_{ag} is agriculture to traffic elasticity, ϵ_{tc} is transport cost to agriculture production elasticity RUC_o is baseline road user cost and ΔRUC^i is reduction of road user cost by intervention i .

$$Tr_y^i = Tr_{y-1}^i * \left(tg + \epsilon_{ag} * \left(\epsilon_{tc} * \frac{\Delta RUC^i}{RUC_o} \right) \right) \quad (5)$$

We detail below the benefits attributed to each of the interventions.

Upgrade of surface treatment

When roads are paved, the road user cost is assumed to be 0.23 \$/km (equivalent to an IRI of 4). When the paved road is close to an agriculture cluster, it is assumed that agriculture production increases by 2.7 points for each 10 point of decrease on road user cost and that the traffic will increase following equation 5 introduced above.

Disruptions are reduced as new drainage structures (culverts) have been put in place to accommodate the new paved road. For instance, an unpaved road was disrupted with 50cm of water on top of the road surface while the paved road can drain 80cm before the road is disrupted (as it is assumed that a new culvert can drain the rainfall from a 20-year return period event). Damages from floods on the infrastructure are considerably lower and so is the repair cost as it is assumed that the condition rate (used in equation 1) is set to 1.

Upgrade to gravel road

Here it is assumed that damaged roads are rehabilitated to restore the initial design. Most of the roads in Zambezia and Nampula are in poor or bad condition due to deficient maintenance and periodic maintenance so this intervention would upgrade the earth road to a gravel one in good conditions. The road user cost is thus assumed to be 0.27\$/km (equivalent to an IRI of 7). The surface and class type are not changed. Like the previous intervention, when the gravel road is close to an agriculture cluster it is assumed that agriculture production would increase using the 2.7/10 relation and thus traffic increases using an elasticity that ranges from 0.5 to 1.5.

Flood damage on the infrastructure is slightly lower as the condition of the road is higher and the costs of repair are lower as it is assumed that the condition rate (used in equation 1) is set to 1. Disruptions caused by flood are not reduced as no intervention on the culverts or bridges is done.

Rehabilitation of earth roads

Here the road user cost is reduced to 0.3\$/km because of improving the condition of the roads through better maintenance and reducing its IRI to 9. When the earth road is close to an agriculture cluster, it is assumed that agriculture production increases by 2.7 and thus we assume traffic increases using an elasticity that ranges from 0.5 to 1.5.

This intervention includes cleaning up culverts as part of rehabilitation procedures. Most culverts have a deficit in maintenance and the drainage capacity is dramatically reduced due to sedimentation or growth of vegetation both up and downstream the culvert. Damage from flood and consequent disruption are thus assumed to be lower as the drainage capacity of culverts is maximized as a consequence of cleaning up the culverts. The drainage capacity is set to the original design standard so that more water can go on the road before it is disrupted. The damage on the surface will be consequently lower as the water level on top of the road is reduced thanks to the increase in drainage capacity.

Clean and repair bridges

It is important to keep bridges in good condition to reduce repair cost after a flood event. However, most bridges in those areas are in poor or bad condition due to the lack of regular and periodic maintenance. They are thus more vulnerable to floods and will suffer more damages than good or fair condition bridges. Here it is assumed that damage from flood onto the bridges can be considerably reduced because of restoring the original condition of the bridge. Disruption is significantly reduced as well because of cleaning up the bottom of the bridge, maximizing the drainage capacity of the bridge to design standards. For example, a bridge currently has a clearance of 170 cm, after this intervention the bridge will be able to drain up to 200cm (equivalent to a 50-year event – the design standard) because of cleaning the sediments/debris that were taking up to 30 cm. Here the road user cost is unchanged as it is assumed that this intervention does not have any impact on the surface of the road.

This section assumes that bridges are designed properly and therefore they do not collapse or are not washed away. At the same time, it simplifies the possible damages, as it only considers damage from water level overtopping the bridge superstructure; it does not include possible failure due to scour or damage on the abutments. This simplicity goes accordingly to the amount of collected data on the bridges – it was not possible to obtain any information regarding the condition of the bridges. We acknowledge that this model is simplistic and can lead to optimistic results. Field experience in Mozambique has demonstrated that many bridges have failed due to poor design on either the piles, abutments or connections between piles and beams with water level that the bridge should be able to withstand if designed properly.

Replacing culverts

Damage from flood on the infrastructure is considerably reduced as new culverts are put in place. The new culvert is assumed to have a design standard twice as large as the original culvert. Disruption is significantly lower as the new culvert can take higher levels of flood. Most culverts are designed for a 10-year event, the new culverts will be able to drain a 20-year event rainfall. In this intervention, the road user cost is unchanged as it is assumed that this intervention does not have any impact on the surface of the road.

The unit cost for each intervention can be found in the annex.

Cost-benefit analysis

A net present value is calculated for each intervention. The decreased number of isolated trips is calculated as well but it is not included in the net present values as it is challenging to give a dollar value to disrupted trips. The net present value (NPV) for intervention i follows the equation below:

$$NPV^i = \left(\sum_{y=1}^{20} \frac{ME_y^0 + EAD^0 + RUC^0 * Tr_y^0 + EAUL^0 * Tr_y^0}{(1+d)^{y-1}} - \sum_{y=1}^{20} \frac{ME_y^i + EAD^i + RUC^i * Tr_y^i + EAUL^i * Tr_y^i}{(1+d)^{y-1}} \right) - CI^i \quad (6)$$

Where ME is maintenance expenditure, EAD is expected annual damage, RUC is road user cost, TR is traffic volume, EAUL is expected annual user losses, CI is capital cost of intervention, d is the discount rate and y the years going from 1 to 20. The cost is different for each of the interventions. Each of the interventions includes periodic and recurrent maintenance that happens at different times during the life-cycle. For instance, a surface treatment road will include periodic maintenance every 9 years, while a gravel road will be maintained every year and an earth road every 4 years (values can be found in the annex and were provided by ANE). The benefits are calculated every year as described in the previous section.

To capture the uncertainty that may affect the performance of some of the interventions, we calculate the NPV of each intervention in 2,000 scenarios, combining values on:⁵

- Climate projections: current, low, medium and high
- Flood duration, -50% to +50% increase compared to the results of the hydrological model⁶
- Traffic growth in the absence of interventions, 0 to 6%⁷
- Traffic growth to agriculture increase elasticity, 0.5 to 1.5
- Discount rate, ranging from 3 to 12%
- Repair time, -50% to +50% of original
- Capital Cost, -50% to +50% of original
- Bridge Repair, -50% to +50% of original

Each of the selected districts has different characteristic and vulnerabilities. For this reason, each district may require a unique combination of the five interventions above in each of its link of the road network, that will maximize the net present value and increase robustness of the road network. Some of these combinations will be: (1) surface treatment to the most vulnerable road and ensure proper maintenance on the rest, (2) repair bridges in most critical link and rebuilt culverts in secondary roads, (3) upgrade to gravel the most critical road and ensure maintenance on secondary road, (4) upgrade to gravel secondary roads only or (5) repair and replace culverts in most critical links only – other combinations may be suggested here by the team.

Once we calculate the NPV of several investment combinations for each of the 2,000 scenarios, we will look for those conditions that are the most robust, that is that have a high NPV under many future conditions.

Robustness analysis

There are many ways of testing the robustness of an investment plan:

⁵ We use a Latin Hypercube Sampling (LHS) method for generating the 2,000 scenarios.

⁶ SSBN developed the flood maps and the hydrological model that calculated water levels and flood duration (more details about the model are in the annex). Flood durations are however difficult to assess in the hydrological model, so we assume it can vary.

⁷ The projected GDP growth for 2018 in Mozambique (Mahdi et al. 2016) is calculated at 6.5%. Traffic and agriculture are expected to grow at a similar rate as GDP. The range of uncertainty applied in these variables is intended to capture the uncertainty on GDP growth.

Identifying factors of failure (or success)

One simple metric may be the number of scenarios in which the NPV is positive. The conditions under which the NPV is not positive can also be analyzed to identify the vulnerabilities of the investment.

To do so, we apply scenario discovery methods for identifying conditions that characterize the vulnerabilities of the proposed investment options. Scenario discovery uses a statistical cluster-finding algorithm to provide concise descriptions of the combination of future conditions that lead a strategy to fail to meet its objectives (Bryant and Lempert 2010).

The description of these conditions helps focus decision makers' attention on the most important uncertain future conditions to the problem at stake and discuss the acceptability of the risks involved with the various options available.

Calculating regret

Another approach is to minimize the maximum regret that each investment can lead to. The choice of this metric assumes a risk averse client, who wants to avoid the worst-case scenario. If needed, we could also explore other metrics. We calculate the regret of each option in each scenario. The regret is defined as the difference in performance of that option compared to the best option, for that scenario.

If i' are all the options considered, and using NPV of the option as the performance criteria, the regret of an option i in the future state of the world s is defined by:

$$\text{regret}(i, s) = \max_{i'} (NPV(i', s) - NPV(i, s)) \quad (7)$$

We can then identify the option that minimizes the maximum regret across a wide range of possible futures. The most robust option therefore is the one that solves:

$$\min_i (\max_s (\text{regret}(i, s))) \quad (8)$$

One way to avoid depending on extreme scenarios is to compare the regret of each project to the regret of not implementing the project. In that case, to find the most robust option one would solve:

$$\min_i \left(\frac{\max_s (\text{regret}(i, s))}{\text{regret}(\text{do nothing})} \right) \quad (9)$$

Results: Murrumbala, Zambezia

The first district (Murrumbala in Zambezia) has been selected based on the prior prioritization exercise that included redundancy analysis, current agriculture production, proximity to agriculture or fishery clusters, poverty rates and vulnerability to flooding events. Table 2 summarizes the existing road infrastructure in this district. The total length of road and the number of bridges come from a database provided by the road administration agency in Mozambique (ANE) and include the unclassified road network surveyed and geo-located in a joint effort between ANE and the World Bank. The number of culverts is estimated based on the intersection between the road network and tributary rivers. The estimation has been calibrated with data collected on the field for some roads. It is an under-estimation and it is likely that more culverts are to be found in this district.

Table 2: Summary of existing road infrastructure

District Name	Province	Total Km paved	Total Km unpaved	Total Km primary	Total number of Bridges	Estimated Culverts*
Morrumbala	Zambezia	5	463	8	13	12

Figure 9: Map of the existing road infrastructure in Morrumbala

Based on discussions with local stakeholders during two workshops held in January 2017 in Quelimane and Nampula, we identified five different investment scenarios in each district. Each of the five combinations of investment is a combination of the five engineering solutions introduced in the methodology section. The investments were constrained to a total of approximately US\$15 million. Table 3 summarizes the five investment scenarios for Morrumbala. The names of the roads are the current nomenclature used by ANE and are shown in the map in Figure 9.

Table 3: Summary of investment scenarios

Murrumbala								
		Paving	Gravel	Partial Rehab	Bridge	Culverts	Initial Capital Cost	Life-Cycle Cost (Median)
Investment 1	RoadID	N322 (partial – 45km)		N322 (rest), R652, R1107, R650 (rest), R1110, R1109, NC				
	Length	45	0	551	0	0	15	18
Investment 2	RoadID	R652 (partial – 60km)		N322, R652 (rest), R1107, R650, R1110, R1109, NC				
	Length	66	0	530	0	0	15	19
Investment 3	RoadID			N322, R652, R1107, R650, R1110, R1109, NC	N322, R652, R1107, R650, R1110, R1109, NC	N322, R652, R1107, R650, R1110, R1109, NC		
	Length	0	0	596	13	17	22	24
Investment 4	RoadID		R650 (partial – 150km) and R652 (partial – 60km)	N322, R652 (rest), R1107, R650 (rest), R1110, R1109, NC				
	Length	0	213	383	0	0	11	19
Investment 5	RoadID		N322, R652 (rest), R1107, R650 (rest), R1110, R1109, NC	R650 (partial – 150km) and R652 (partial – 60km)				
	Length	0	383	213	0	0	18	29

We calculated the net present value for each of the five investment combinations in 2,000 scenarios following equation 6 above.

Figure 10 Breakdown of the benefits for each combination of interventions in the 2,000 scenarios discounted over 20 years

Figure 10 shows the different benefits of each intervention in the 2,000 scenarios. All costs and benefits are discounted to 2016 dollars and include life-cycle cost over 20 years. The highest potential benefits are for avoided flood risk to users (reduction of EAUL) and reduction of risk to the infrastructure (EAD), which can go up to almost 100 million dollars. Benefits in terms of RUC decrease, maintenance savings are one order of magnitude lower and bring a few tens of million dollars in benefits.

Interestingly, different interventions bring different kinds of benefits: improving the drainage structures (Inv. 3) yields the biggest benefits in terms of avoided repair (reduction of EAD) while graveling roads increases maintenance expenditure leading to a negative value of maintenance savings. Repairing and rehabilitating bridges is the most expensive action after a flood occurs. Therefore, investing proactively on bridge and culvert repair and cleaning will result in high benefits in avoided repair (and reduction of

expected annual damages, EAD). The benefits for the users of the roads are the highest for investment 5 as more than 380 km are graveled, followed by investment 4 and investment 2. Improving drainage structure mostly benefits the road agency rather than the users.

Investments 4 and 5 can result in increased maintenance costs (Figure 10). This is because we are assuming that the investment will follow high standards of maintenance during the 20 years of the life-cycle, meaning keeping a good condition of the road surface. For those investments (upgrading to gravel roads) this requires a high frequency of periodic maintenance. On the other hand, the baseline scenario assumes that the maintenance is set to a low standard.

Figure 11 Total cost (left) and total benefits (right) discounted over 20 years in each of the 2,000 scenarios

Figure 12 Benefit cost ratio and avoided isolated trip per dollar spent in each of the 2,000 scenarios

Figure 12 (left panel) shows the benefit-cost ratio of each intervention, aggregating all benefits shown in Figure 10 and dividing by the cost (total costs and total benefits are shown in Figure 11). The cost includes

initial capital investment, recurrent and periodic maintenance. The five interventions initial investment costs are around US\$15 million, with investment 3 being the highest. When this initial investment is aggregated with the recurrent and periodic maintenance over the 20 years, investment 5 is substantially more expensive than the others. The reason is that gravel roads require more frequent periodic maintenance in order to maintain the initial condition set to a high standard.

Figure 12 (right panel) shows the number of avoided isolated trips for each intervention, divided by the cost of the intervention. Here the third intervention is also the one that reduces the highest number of isolated trips per dollar spent.

Investment 3 is the best (i.e. has the highest NPV) under 98% of the scenarios, and it has a positive NPV under 95% of the scenarios. We look for the conditions under which investment 3 has a positive NPV using a scenario discovery technique called PRIM (Bryant and Lempert 2010). We find that the NPV of investment 3 is positive if three of the conditions are met together: (i) if the discount rate is lower than 10.5%, (ii) the cost of bridges is greater than 60% of current estimates and (iii) the capital cost does not exceed 140% of the current estimate. 100% of the scenarios that meet those criteria have a positive NPV, and 70% of the scenarios that have a positive NPV meet these criteria.

The explanations for these results are as follows. The main benefits of investment 3 come from avoided flood disruption risk (reduction of EUAL) and the reduction of damage to the infrastructure (EAD). On the other side, most of the cost comes from repair, cleaning and retrofitting of bridges. Most of the expenditure happens upfront while the benefits are distributed across the 20 years of the life-cycle, therefore high discount rates will lead to lower net present values. If this is combined with low cost of repairing bridges, the discounted benefits from avoided cost after floods will be much smaller, as it may be more beneficial to repair the bridge after a flood than invest proactively upfront. Finally, the capital cost variable affects not only bridges but all the other interventions. So, if lower benefits due to (i) and (ii) happen together with higher capital cost, the NPV of investment 3 may become negative.

As explained before, even if we cannot say much about the likelihood of all these uncertainties, it is unlikely that the cost of repairing bridges will decrease dramatically over the next decade, while other costs increase, therefore under reasonable conditions investment 3 is always a good option.

To go further, we calculate the regret that each investment can bring in each of the scenarios. The regret is calculated as the difference between the NPV of the investment and the NPV of the best investment under this particular scenario. Figure 13 shows that investment 3 brings the lowest maximum regret, meaning that even when it is performing less well than investment 5 the loss is minimal. The maximum regret of investment 5 is higher because this investment misses the potentially very high benefits of investment 3 in terms of avoided risk (reduction of EUAL and EAD) under some scenarios. These results mean that it is better to invest in investment 3 under conditions more suitable for investment 5, than the other way around. The analysis above therefore suggests that investment 3 is the most robust investment for Murrumbala.

Figure 13 Regret of each investment in all 2,000 scenarios.

Table 4 Maximum regret for each of the five investment scenarios

<i>Test Robustness</i>	<i>Investment 1</i>	<i>Investment 2</i>	<i>Investment 3</i>	<i>Investment 4</i>	<i>Investment 5</i>
<i>Maximum regret – over 20 years in MUSD</i>	104.1	102.8	16.8	106.3	128.8

If budget is not available for investment 3 (\$22 million), the second-best option may not be that straightforward. Investment 5 might be considered because it is the best option in a few of the scenarios. However, the maximum regret of investment 2 is lower than the regret of investment 5. The NPV of investment 2 is higher than that of investment 5 in 85% of the scenarios. In 40% of the scenarios the NPV for investment 2 is positive while only 28% for investment 5. In terms of non-monetized benefits, investment 2 always has larger saved trips per dollar ratio, and total number of trips saved than investment 5. If we go a bit further in the analysis, we find that the NPV of investment 2 is positive for (i) climate change current or low, (ii) traffic growth above 0.7% and (iii) capital cost below 145% of current estimates. The two last conditions are very likely to occur leaving climate change as the switching parameter for investment 2 being profitable. Investment 2 is the second most preferable and robust investment for Murrumbala, however under medium or high increase in flood intensity because of climate change, additional interventions such as bigger drainage structures will be needed to reduce flood risk.

Results: The other districts

We repeat the analysis above for Memba, Erati (new name to Namapa district) and Monapo districts in Nampula, and Maganja and Pebane in Zambezia. Table 5 summarizes the findings for each of the 6 districts. It identifies the most robust intervention, from a set of 5 interventions in each case (see annex for list of interventions in each district) and evaluates its robustness (last column of the table). High robustness would mean that the selected intervention has the highest NPV in most of the scenarios. On the other side, medium or low robustness means that the selected intervention may have the highest NPV but not always positive.

Given the limited budget per district (approx. US\$15 million) cleaning and repair of bridges together with upgrading the culverts seems to be the most robust intervention in almost every district. Cleaning and repair of bridges and upgrading culverts has a lower capital cost and returns a high benefit mostly in terms of avoided damage to the infrastructure due to flood events. The other types of investment, paving, graveling or rehabilitating, have a higher capital cost and with the constrained budget of US\$15 million very few kilometers of road can be upgraded. Additionally, the low traffic volumes in these regions of the country make it harder to justify these last interventions.

Table 5: Summary of most robust intervention in each of the 6 selected district

Province	District	Investment	Description	Robustness
Zambezia	Murrumbala	Inv 4	Clean and repair all bridges and upgrade all culverts	Very high
	Maganja	Inv 2	Clean and repair bridges in N324	Medium (good only if climate change is high)
	Pebane	Inv 3 + Inv 4	Clean and repair bridges in N324 + upgrade all culverts	High for Inv 4, medium for inv 3
Nampula	Memba	Inv 3	Clean and repair all bridges and upgrade all culverts	Very high
	Namapa/Erati	Inv 2	Clean and repair all bridges and upgrade all culverts	Very high
	Monapo	Inv 3 + Inv 4	Paving R700 & R1153 + Clean and repair all bridges and upgrade all culverts	Very high for Inv 4, medium for Inv 3 (good only if traffic growth is high)

In order to better understand the robustness of the interventions across each of the provinces, we have plotted together the distribution of net present values for each of 5 interventions in each of the 3 districts (Figure 14 and Figure 15) – with each color corresponding to a district. The distributions of NPV are shown in the boxplot using the left axis. The initial investment or capital cost for each intervention is plotted with a blue star and using the right axis.

In the province of Zambezia (Figure 14), investment 1B in Murrumbala is an addition to the ones previously described and represents the pavement of the entire N322. The initial investment is US\$30 million approximately, so outside the initial budget limitation. The reason to add this investment is to test

if the constraint of US\$15 million is preventing larger overall benefits. The investments have been sorted by their minimax value (equation $\min_i (\max_s (\text{regret}(i, s)))$ (8). This is equivalent to being sorted out by robustness. Therefore, the interventions on the left are more robust than the ones on the right. The two horizontal lines are for reference only; the black line at NPV equal to 0 and the blue line at initial investment equal to US\$15 million.

Figure 14: Net Present Value distribution for 15 interventions in 3 districts in Zambezia

The top five interventions are in the same district; Murrumbala. Murrumbala is a district with high agriculture potential, higher average daily traffic and at the same time high exposure to floods due to its proximity to the Zambezi River. Most interventions in this district project higher benefits due to this set of conditions, leading to higher robustness when compared to other interventions elsewhere. On the other side, it seems that interventions in Pebane do not bring large benefits; with negative NPV values in all scenarios.

Figure 15: Net Present Value distribution for 15 interventions in 3 districts in Zambezia

In Nampula (Figure 15), the top three interventions are located one in each of the three districts. The three top interventions are the same; *cleaning and repair bridges plus upgrading culverts*, with Memba and Namapa districts having the largest NPV and highest robustness. While the high robustness of the interventions does not seem to be as clearly correlated with the location as in Zambezia, if looking at the 15 interventions, the trend may suggest that interventions in Monapo (in green) are more robust than the ones in Memba (red), while interventions in Namapa (yellow) are concentrated in the lower end. Monapo is located in the Nacala corridor, the busiest transport corridor in the province. This district also has large current and potential agriculture production. Therefore, interventions in this district bring larger benefits. Apart from the top three interventions in Nampula, all the other interventions have a median NPV below zero (thicker line in the middle of the box) and in most cases, even the 95th percentile is below zero.

These results lead as to conclude that in those districts the traffic volumes are so little that reducing road user cost does not justify economically most of the investments. However, we have found in this paper that some of these interventions could be justified by looking at the non-monetized benefit in terms of avoided disruption and reduced isolation of trips between communities. Additionally, the other possible conclusion is that to achieve positive NPVs for paving or graveling roads in these districts, the initial investment needs to be larger (as it is seen in investment 1B in Murrumbala in Zambezia).

Discussion: Application of this study to bank operations in the transport sector

Section I of the study has provided a geospatial approach to prioritize road investments. The methodology has proven successful to quantitatively and transparently identify priority investment for rural roads. This methodology could be implemented for other types of networked infrastructure such as railroads, electric gridlines or water pipelines. This study can provide TTLs and clients with the needed data-driven support to establish objective discussion on what areas and what infrastructure should be prioritized under a constrained budget.

Section II provides two additional components to the economic analysis required during project appraisal. First, it provides a broader perspective of the benefits of the investment, as it incorporates climate adaptation co-benefits, in terms of reduced damage to infrastructure and reduced travel disruption cost. For reduced

travel disruption costs, it presents a new method to quantify the systemwide benefits of improving the resilience of the transport network. Using a network approach, it quantifies the road user cost benefits from upgrading second-best routes. It quantifies as well non-monetized benefits in terms of reduction of isolated trips. Second, it presents an innovative method, embedded in decision-making under uncertainty techniques, to deal with deep uncertainty in many economic factors. This method identifies combinations of variables that make investments fail and it helps decision-makers select interventions that are robust to a range of future conditions.

This new methodology is applied to road interventions in rural Mozambique. Five different sets of interventions are proposed for each of the six districts selected for the analysis. Among the different interventions in the study area, and given the limited budget per district, investing in bridges and culverts is always the most robust option. In some cases, paving seems to be the best option when the paved road is long (but in this case the cost is higher than the available budget, like investment 1B in Murrumbala). When incorporating systemwide benefits, paving or graveling secondary routes to increase redundancy is not always profitable, as traffic volumes are low and alternative routes may get flooded as well. In some districts the NPV of interventions is positive only under some conditions (e.g. high climate change), however we have demonstrated that they could be justified using non-monetized benefits, such as reduction of isolated trips.

Incorporating network benefits has proven to be very effective to identify interventions that improve the overall performance of the network under adverse conditions – like interventions that increase the redundancy of the network. These interventions increase the resilience of the network because they improve second-best routes when the main one is disrupted. This type of benefit would not have been taken into consideration with a traditional project-level economic analysis.

Decision-making under uncertainty techniques are particularly useful in the context of transport investment. Climate change is not the only factor in the transport economic analysis which is a deep uncertainty: traffic demand forecasting and traffic growth play a major role in the analysis and are uncertain and fluctuant during the lifecycle of the intervention. DMDU techniques, as demonstrated in this paper, help identify the most robust interventions. DMDU identifies the combinations of factors that would make the interventions fail. With all the information provided through the different components of the DMDU method, the decision-maker can suggest possible alternatives to the current interventions analyzed, with the goal to improve their performance under the conditions identified as risky.

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Annex

Additional maps and figures

Figure 16: Nodes distribution across Mozambique

Figure 17: Traffic map in AADT (average annual daily traffic)

Figure 18 Potential Agriculture production in Millions USD and selected agriculture clusters for the network analysis

Figure 19: Road that are not included in the analysis because they do not give access to any node

Figure 20: Criticality map based on distance from an agriculture or a fishery production cluster. Using minim distance between any point on the road and the closes agriculture or fishery cluster (see other figure for location of clusters)

Figure 21: Criticality map based on poverty rates

11	airport	Chimoio	-19.1513	33.42896
12	airport	Chinde	-18.6167	36.4
13	airport	Chokwe	-24.5206	32.96528
14	airport	Cuamba	-14.8175	36.52833
15	airport	Gurue	-15.5	37.01667
16	airport	Ibo	-12.3333	40.58333
17	airport	Inhambane	-23.8764	35.40854
18	airport	Inhaminga	-18.4	35
19	airport	Lichinga	-13.274	35.26626
20	airport	Luabo	-18.4	36.1
21	airport	Lumbo	-15.0274	40.66943
22	airport	Majanga Da Costa	-25.35	32.21667
23	airport	Maputo	-25.9208	32.57261
24	airport	Marromeu	-18.2908	35.94528
25	airport	Mocimboa Da Praia	-11.3618	40.35487
26	airport	Moma	-16.75	39.21667
27	airport	Montepuez	-13.1219	39.0528
28	airport	Mueda	-11.6729	39.56314
29	airport	Nampula	-15.1056	39.2818
30	airport	Nangade	-11.0833	39.6
31	airport	Palma	-10.75	40.471
32	airport	Pebane	-17.25	38.18333
33	airport	Pemba	-12.9868	40.52249
34	airport	Quelimane	-17.8555	36.86911
35	airport	Tete Chingodzi	-16.1048	33.64018
36	airport	Vilankulo	-22.0184	35.3133
37	airport	Xai Xai	-25.0378	33.62722
38	border_crossing	Giriyondo	-23.5838	31.65788
39	border_crossing	Ressano Garcia	-25.4425	31.98466
40	border_crossing	Ponta do Ouro	-26.8643	32.82927
41	border_crossing	Pafuri	-22.449	31.315
42	border_crossing	Milange	-16.0808	35.73983
43	border_crossing	Mandimba	-14.3738	35.60261
44	border_crossing	Marka	-17.1277	35.23009
46	border_crossing	Dedja	-14.4002	34.32504
47	border_crossing	Goba Fronteira	-26.2575	32.08001
48	border_crossing	Namaacha	-25.9891	31.99828
49	border_crossing	Chiqualaquala	-22.0714	31.67895
50	border_crossing	Espungabera	-20.423	32.75689
51	border_crossing	N of Chimanimani Transfrontier Park	-19.5386	32.83959
52	border_crossing	Machipanda	-19.006	32.71317
53	border_crossing	Changara	-16.9691	32.82263
54	border_crossing	Chifunde	-14.3028	32.35003
55	border_crossing	Negomano (Unity Bridge)	-11.4199	38.49394
56	border_crossing	Niassa (Unity Bridge 2)	-11.5781	35.42965
57	major_city	Tete	-16.161	33.58398
58	major_city	Lichinga	-13.3061	35.24865
59	major_city	Montepuez	-13.1253	38.98959
60	major_city	Pemba	-12.9624	40.50866
61	major_city	Nampula	-15.1171	39.26472
62	major_city	Cidade de Nacala	-14.5395	40.6794
63	major_city	Ant?nio Enes	-16.2295	39.90803
64	major_city	Chimoio	-19.1124	33.47888
65	major_city	Machaze	-20.8261	33.36796
66	major_city	Quelimane	-17.8729	36.88869
67	major_city	Beira	-19.8283	34.85038
68	major_city	Chokw?	-24.5315	32.9879
69	major_city	Chibuto	-24.6894	33.52957
70	major_city	Xai-Xai	-25.0443	33.64263
71	major_city	Matola	-25.9483	32.46552
72	major_city	Maputo	-25.9508	32.57902
73	major_city	Maxixe	-23.8654	35.34628
74	major_city	Cuamba	-14.8001	36.5338

75	major_city	Gurue	-15.4715	36.981
76	agricultural_potential_cluster		-17.3884	35.68478
77	agricultural_potential_cluster		-16.3542	35.69249
78	agricultural_potential_cluster		-16.7177	37.46737
79	agricultural_potential_cluster		-16.6953	37.05021
80	agricultural_potential_cluster		-16.551	36.79144
81	agricultural_potential_cluster		-16.1563	37.03103
82	agricultural_potential_cluster		-16.0569	37.41265
83	agricultural_potential_cluster		-15.7311	36.99599
84	agricultural_potential_cluster		-15.6417	36.49144
85	agricultural_potential_cluster		-15.6914	39.8331
86	agricultural_potential_cluster		-15.3156	39.54143
87	population_cluster		-16.7688	39.19287
88	population_cluster		-16.2188	39.899
89	population_cluster		-16.1364	39.58546
90	population_cluster		-16.0776	39.1558
91	population_cluster		-15.9013	39.39341
92	population_cluster		-15.8485	39.00253
93	population_cluster		-15.7173	39.34171
94	population_cluster		-15.6098	39.94208
95	population_cluster		-15.4615	38.68067
96	population_cluster		-15.1145	39.2599
97	population_cluster		-15.2251	40.48094
98	population_cluster		-15.205	38.69125
99	population_cluster		-15.0609	40.31833
100	population_cluster		-14.9737	38.81792
101	population_cluster		-15.0229	38.04798
102	population_cluster		-14.9633	40.65953
103	population_cluster		-14.9732	39.84122
104	population_cluster		-14.9433	38.32017
105	population_cluster		-14.9003	40.18264
106	population_cluster		-14.915	39.98874
107	population_cluster		-14.9536	39.64371
108	population_cluster		-14.9171	40.30577
109	population_cluster		-14.8213	40.50012
110	population_cluster		-14.7465	40.44868
111	population_cluster		-14.7571	39.95537
112	population_cluster		-14.6838	40.55488
113	population_cluster		-14.7036	38.40036
114	population_cluster		-14.6517	38.89216
115	population_cluster		-14.4808	39.98633
116	population_cluster		-14.4776	39.81684
117	population_cluster		-14.5402	40.68933
118	population_cluster		-14.3473	40.58002
119	population_cluster		-13.9783	40.19629
120	population_cluster		-13.7159	39.82436
121	population_cluster		-17.9761	35.71047
122	population_cluster		-18.0611	36.75812
123	population_cluster		-17.5529	36.79404
124	population_cluster		-17.4948	37.02873
125	population_cluster		-17.3298	35.59372
126	population_cluster		-17.3143	37.5095
127	population_cluster		-17.3029	38.05659
128	population_cluster		-17.0083	37.62242
129	population_cluster		-16.9579	37.8577
130	population_cluster		-16.8368	36.98225
131	population_cluster		-16.7029	38.95348
132	population_cluster		-16.4949	36.82526
133	population_cluster		-16.1435	37.38556
134	population_cluster		-16.0966	35.76607
135	population_cluster		-15.752	36.78395
136	population_cluster		-15.7325	38.26602
137	population_cluster		-15.6242	37.68543

138	population_cluster	-15.4697	36.98344
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Figure 23: Correlation between IRI and Road User Cost (RUC)

Figure 24: Graphs using data behind criticality maps (road links that do not produced disruption have not been plotted)

Figure 25: Exposure of 1 in 5 flood event

Figure 26: Exposure of 1 in 100 flood event

Figure 27 District vulnerability map based on expected annual losses on the road infrastructure including primary roads

Figure 28 Risk map at district level including primary roads

Details of the methodology

Traffic

The traffic between each Origin-Destination pair is estimated using a simplified version of the standard four-step model for traffic forecasting, also called Travel Demand Model (TDM). The four traditional steps are:

1. **Trip generation:** identifying the number of trips to be generated by each node
2. **Trip distribution:** locating the destination node for each generated trip
3. **Mode choice:** splitting the trips between each OD among different transport mode
4. **Trip assignments:** predicting the route that each trip is going to take

For the purpose of this study and based on the characteristics of the study area, we are only looking at traffic by 4-wheel vehicles. We are assuming that each node generates a number of trips equal to the sum of the traffic on all the roads linking each node. In order to distribute the trips and create the OD matrix, we use a friction model using traditional formulation:

$$T_{ij} = P_i \left[\frac{A_j * F_{ij} * K_{ij}}{\sum_j A_j * F_{ij} * K_{ij}} \right]$$

Where:

- T_{ij} = number of trips that are produced in node I and are attracted to node J
- P_i = total number of trips produced in node I
- A_j = number of trips attracted to node J
- F_{ij} = friction factor between node I and J (normally inverse function of travel time or travel distance)
- K_{ij} = a socioeconomic adjustment factor for the interchange IJ

In order to simplify the formulation, the number of trips produced and the number of trips attracted are equal to the sum of traffic count (AADT) for all the roads linking a node. The friction factor (F) is calculated as an aggregation of the road user cost values (obtained for each link from HDM4 based on road condition

and length) for all the links in the least cost route between each pair of nodes. The adjustment factor (K) is set to 1 for simplification.

The mode choice step is skipped in this model as we are only interested in traffic by vehicle. Finally, the trip assignment is calculated using a least cost path algorithm⁸ to identify the optimal route between each pair of nodes. We use again the HDM4 value of road user cost in each link as the cost to be minimized.

Through the four steps of the TDM model we obtain a trip matrix between each pair of OD - in this project a 138 by 138 matrix.

Flood maps

Coastal surge hazard layers were produced for Mozambique under both current and future climatologies, using state of the art hydrodynamic simulations of the Mozambique coastline. In brief, SSBN used available tidal data to provide an understanding of magnitude and duration of surge events that may be experienced along the coast. These data were used to derive proxy hydrographs at different return periods. These hydrographs were then implemented as boundary conditions in a large scale hydrodynamic model. Each of these simulations were conducted on Satellite Radar Topography Mission (SRTM) data, as this has been found to be the most suitable terrain data set for use in hydraulic modeling. This terrain data set was subject to significant pre-processing to remove errors associated with vegetation, urban-areas and noise. River channels and flows were also explicitly represented in the coastal modeling structure.

The simulations under future climate conditions were undertaken by combining the derived coastal hydrograph with IPCC projections of sea-level rise for the region. The final output of the work is coastal flood hazard layers at ~90m resolution, under both current and future climate conditions.

Fluvial flood hazard layers were derived from the SSBN Global Flood Model (GFM). GFM is a large scale hydrodynamic modeling structure designed to enable flood modeling in data scarce regions. The model itself is a fully 2D hydraulic model, using custom processed terrain data to provide flood hazard data at ~90m resolution. It is driven by a global Regional Flood Frequency Analysis (RFFA) that has been derived from the gauged flow records of thousands of rivers across the world.

The SSBN GFM produces flood hazard data that have a 3-arc second resolution (~90m). All simulations are dynamic full 2D simulations, with the exception of very steep areas in which bespoke routing tools are used as the shallow water equations are not valid under these conditions. A sub-grid channel network is implemented that allows the dynamics of channels smaller than the grid scale to be simulated, ensuring that in-channel flow is explicitly represented for all channels, regardless of size. Both the RFFA and GFM methods have been subjected to independent peer review and are published in top academic journals.

The SSBN GFM structure was used to provide realizations of flood hazard under future climate scenarios and potential land use changes. Firstly, the simulations of future climate scenarios were undertaken by perturbing the discharge values derived from the regionalized flood frequency analysis. This process was informed using the latest projections of changing climatology for the region taken from the IPCC AR5 projections and from recent studies undertaken in the region. The projections used represented changing precipitation values; a linear relationship between changing rainfall amounts was therefore assumed. The simulation of future climatologies was implemented as a modeling mass balance exercise, whereby they are changing the amount of water entering the model domain as defined by peer reviewed studies.

⁸ Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische mathematik*, 1(1), 269-271.

The simulation of flooding given future land use changes was undertaken by changing the flood hydrograph generated by the SSBN GFM framework. Studies examining the relationship between land use changes and flood frequency behavior were used to define the perturbations. More specifically, changes to rainfall run-off coefficients and flood wave attenuation, as a result of deforestation, were used to infer changes both to the volume of water and to the time to concentration values for the derived hydrograph. This simplified approach assumes that there is a linear relationship between deforestation extent and changing hydrograph characteristics. Moreover, it assumes that the defined perturbations scale equally with changing catchment sizes, i.e. changes that have been described for small-scale study catchments will remain the same for larger catchments. Such assumptions are necessary to enable the simulation of deforestation effects over large scales and over multiple catchments given the budgetary and time constraints of the project.

Simulations under future climate conditions were undertaken using the output from the World Bank Climate Change Knowledge portal (<http://climatewizard.ciat.cgiar.org/wbclimateanalysisistool/>). Specifically, changes to the maximum 5-day rainfall accumulations, for the 2050 time-horizon, were used to derive future model boundary conditions. Three scenarios, taken from the model ensemble were used under the RCP8.5 climate scenario; these were the ensemble lowest, mean and highest. The changes were implemented by taking the distributed change masks for Mozambique and calculated the mean change across the country, these changes were then used to perturb the boundary conditions of the fluvial hydraulic model structure.

	Low	Mean	High
Change Δ(%)	-4.2	+5.6	+16

Table 1: Changes implemented for future fluvial simulations

For the pluvial simulations, the distributed masks of future change were used directly to perturb the input rainfall masks.

The results from the future simulations outline a wide degree of uncertainty in future flooded area, with estimates of future flooded area ranging by >30%. A significant amplification of lower return period flood magnitude is displayed, with changes to the 5-year hazard layer being more pronounced than the 100year event.

The results also suggest that changes to Pluvial (flash-flood) events will be more pronounced than changes to fluvial (riverine) events. This suggests that off-floodplain, or areas away from well-defined floodplains may be most exposed to changes in future extreme rainfall.

Fluvial&Pluvial	Area (km ²)	Change Δ (%)		
	Current	Low	Mean	High
1 in 5	~67131	-5.24646	9.530619	25.25361
1 in 100	~144720	-3.02653	8.067993	15.67855

Table 2: Changes to flooded area in combined Fluvial/Pluvial hazard layers.

Figure 1: 1 in 100 year hazard layer under current and future scenarios

Unit cost of construction

<i>Design Standards (year)</i>	<i>culvert_paved</i>	<i>culvert_unpaved</i>	<i>bridge_paved</i>	<i>bridge_unpaved</i>
<i>primary</i>	20	20	100	100
<i>secondary</i>	20	20	50	50
<i>tertiary</i>	10	10	50	50
<i>unclassified</i>	10	10	50	50

<i>Cost of Repair in USD</i>	<i>culvert_paved</i>	<i>culvert_unpaved</i>	<i>bridge_paved</i>	<i>bridge_unpaved</i>
<i>primary</i>	10000	10000	40000	40000
<i>secondary</i>	10000	10000	40000	40000
<i>tertiary</i>	10000	10000	40000	40000
<i>unclassified</i>	10000	10000	40000	40000

<i>Time of Repair in HR</i>	<i>culvert_paved</i>	<i>culvert_unpaved</i>	<i>bridge_paved</i>	<i>bridge_unpaved</i>
<i>primary</i>	720	720	4320	4320
<i>secondary</i>	720	720	4320	4320
<i>tertiary</i>	720	720	4320	4320
<i>unclassified</i>	720	720	4320	4320

<i>Cost of Repair in USD/km</i>	<i>paved</i>	<i>unpaved</i>	<i>severity</i>
<i>primary</i>	2000	15000	Low
<i>secondary</i>	2000	15000	
<i>tertiary</i>	2000	15000	
<i>unclassified</i>	2000	15000	
<i>primary</i>	4000	27000	Medium
<i>secondary</i>	4000	27000	
<i>tertiary</i>	4000	27000	
<i>unclassified</i>	4000	27000	
<i>primary</i>	200000	55000	High
<i>secondary</i>	200000	55000	
<i>tertiary</i>	200000	55000	
<i>unclassified</i>	200000	55000	

<i>Time of repair in HR/km</i>	<i>paved</i>	<i>unpaved</i>	<i>severity</i>
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<i>primary</i>	168	1440	Low
<i>secondary</i>	168	1440	
<i>tertiary</i>	168	1440	
<i>unclassified</i>	168	1440	
<i>primary</i>	336	2160	Medium
<i>secondary</i>	336	2160	
<i>tertiary</i>	336	2160	
<i>unclassified</i>	336	2160	
<i>primary</i>	1056	4320	High
<i>secondary</i>	1056	4320	
<i>tertiary</i>	1056	4320	
<i>unclassified</i>	1056	4320	

	<i>Paved (usd/km)</i>	<i>Gravel (usd/km)</i>	<i>Rehabilitation (usd/km)</i>		<i>Clean and Repair Bridge (usd/m)</i>	<i>Upgrade Culvert (usd/un)</i>
	Paved	Unpaved	Paved	Unpaved		
<i>Primary</i>	1000000	320000	60000	6000	5000	44000
<i>Secondary</i>	1000000	215000	60000	6000	5000	44000
<i>Tertiary</i>	550000	215000	60000	6000	5000	44000
<i>Unclassified</i>	550000	215000	60000	6000	5000	44000

		<i>Surface Treatement</i>	<i>Gravel</i>	<i>Rehabilitation of Earth</i>	<i>Baseline</i>
<i>Recurrent</i>	Good	\$ 1,250	\$ 626	\$ 225	\$ 113
	Fair	\$ 1,500	\$ 750	\$ 300	\$ 150
	Poor	\$ 750	\$ 375	\$ 150	\$ 75
<i>Periodic</i>	Good	\$ 8,571	\$ 2,143	\$ 571	\$ 286
	Fair	\$ 8,571	\$ 2,143	\$ 571	\$ 286
	Poor	\$ 8,571	\$ 2,143	\$ 571	\$ 2,857
<i>Interval (years)</i>	Good	9	1	4	8
	Fair	9	1	4	8
	Poor	9	1	4	8

List of interventions

		Maganja						
		Paving	Gravel	Repair	Bridge	Culverts	Initial Cost	LC Cost (median)

1	RoadID		R651, R656, NC/27	N324, NC/22	N324	R651, R656, NC/27	13.5	37
	Length		127	263	3	2		
2	RoadID			all	N324		18	24
	Length			390	6			
3	RoadID		N324	others		N324	8.5	31
	Length		171	219		1		
4	RoadID			all		all	2	8
	Length			390		4		
5	RoadID		others	N324			10	36
	Length		213	177				

		Pebane						
		Paving	Gravel	Repair	Bridge	Culverts	Initial Cost	LC Cost (median)
1	RoadID		N324, N325	others	N324 (only 1)		12.3M	48M
	Length		223	309	1			
2	RoadID		R648	others	R648 (all), N324 (only 1)		8.3M	31M
	Length		89	443	3			
3	RoadID			all	N324 (2 bridges)		10.1M	20M
	Length			532	2			
4	RoadID			all		all	3.2M	14M
	Length			532		13		
5	RoadID		N325, R1108, NC	N324, R648			11.2M	44M
	Length		220	312				

Memba								
		Paving	Gravel	Rehabilitation	Bridge	Culverts	Initial Cost	LC Cost (median)
1	RoadID	R697		others			13	16
	Length	59	0	352	0	0		

2	RoadID	R706, R1153		others			16	19
	Length	76	0	335	0	0		
3	RoadID			all	all	all	14	16
	Length	0	0	411	4	8		
4	RoadID		R697, R1153	R706, others			7	12
	Length	0	136	275	0	0		
5	RoadID		R703, R1152, R1163	R705, others			13	21
	Length	0	276	135	0	0		

		Namapa						
		Paving	Gravel	Rehabilitate	Bridge	Culverts	Initial Cost	LC Cost (median)
1	RoadID		NC13, NC14, NC15, R1166, R706	R705, R1152			10	41
	Length	0	192	286	0	0		
2	RoadID			all	all	all	15	24
	Length	0	0	478	4	12		
3	RoadID		NC13, NC14, NC15	others		NC13, NC14, NC15	7	26
	Length	0	95	383	0	4		
4	RoadID	R706		others			20	32
	Length	97	0	381	0	0		
5	RoadID	R1166		others			19	31
	Length	89	0	389	0	0		

		Monapo						
		Paving	Gravel	Rehabilitate	Bridge	Culverts	Initial Cost	LC Cost (median)
1	RoadID	R1168		others			8	11
	Length	42	0	91	0	0		
2	RoadID	R689		others			11	15
	Length	57	0	76	0	0		
3	RoadID	R1157, R700		R1168, R689			7	9
	Length	34	0	100	0	0		
4	RoadID			all	all	all	3	4
	Length	0	0	133	3	6		
5	RoadID		all				6	18
	Length	0	133	0	0	0		