Resilient Transport Series

CAMBODIA

Geospatial Analysis for Resilient Road Accessibility

WORLD BANK GROUP

GFDRR
Global Facility for Disaster Reduction and Recovery

Cambodia: Geospatial Analysis for Resilient Road Accessibility for Human Development and Logistic Supply

1818 H Street NW

Washington DC 20433

Telephone: 202-473-1000

Internet: www.worldbank.org

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Cambodia:

Geospatial Analysis for Resilient Road Accessibility for Human Development and Logistic Supply

FINAL REPORT

June 2024

WORLD BANK GROUP

GFDRR
Global Facility for Disaster Reduction and Recovery

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1. Introduction

1.1. Aim and Scope of the Report

The primary purpose of this report is to introduce a practical framework to assist the Ministry of Rural Development (MRD) of Cambodia to prioritize its investment and interventions for rural roads in order to achieve climate resilient rural accessibility for poverty reduction, human development, and logistic supply.

The proposed framework is based on two core geospatial models, namely the Flood Disruption Model and the Logistic Supply Chain Model, to collectively identify the most critical and climate vulnerable road sections for prioritized interventions. The Flood Disruption Model simulates the impact of flood disruptions to different rural roads under a 50-year flood scenario and identifies roads where the accessibility loss after flooding results in most damaging impact for rural communities to reach schools, hospitals, job opportunities, and for agriculture products to reach nearby markets. The Logistic Supply Chain Model simulates the disruption of Cambodia's nodes and links and models how supply chain flows get rerouted or blocked, which leads to increase of product prices and shortage of product availability. It quantifies the relative importance of each logistics corridors as well as their rural feeder roads. Combining two models, the proposed framework enables MRD to deploy its limited resources to rural roads that matter the most.

1.2. Audience for this Report

The audience for this report is officials and decision makers at MRD, and other rural road authorities across the developing world which faces the similar challenges in prioritizing rural road investment under increasing climate threat. Development partners and professionals may also benefit from this report in exploring and advising rural road investment planning with their counterparts.

1.3. Methodology and Source Materials

This report and the proposed prioritization framework are based on geospatial modelling works. It builds on and expands previous works in Cambodia, particularly Espinet Alegre et al. (2020), and Colon, Hallegatte, and Rozenberg (2021). Other relevant works include Andres et al. (2018), Krambeck et al. (2019), Quiros, Kerzhner, and Avner (2019), and Rentschler et al. (2019). Rural road data used for the geospatial analysis under this report are provided by MRD, complemented by road network data from Open Street Map (2019). Flood maps for return periods of 5, 10, 20, and 50 years are provided by Deltares. Other key data sources are summarized in section 4.

1.4. Structure of the Report

This report introduces an innovative multi-indicator prioritization framework to assist rural road investment prioritization for resilient accessibility and logistic supply. If focuses on illustrating the rationale of the framework, its underpinning geospatial models, and key results when applied to Cambodia's rural road network.

Following the introduction section,

- **Section 2** provides the basic context of Cambodia's rural road network and the challenge imposed by climate change to rural road investment planning.
- **Section 3** introduces the proposed prioritization framework and how it could assist better prioritization at MRD in practice.
- **Section 4** elaborates how two underpinning geospatial models work, including the data, assumptions, and limitations of each model.
- **Section 5** illustrates key results when the proposed prioritization is applied to Cambodia's rural communes and recommends an indicative list of prioritized rural roads for illustration purpose.
- **Section 6** provides a summary of the main recommendations, next steps for practitioners, and concluding remarks.

2. Cambodia's Rural Road in the Face of Climate Change

2.1. Overview of Cambodia's Rural Road Network

With a total length of more than 47,000 km, rural roads form the backbone of Cambodia's road system, accounting for about 75 percent of the total road network. Rural roads play an essential role for Cambodia's rural population, which represents 79 percent of the total population, to access services, facilities, and economic opportunities.

MRD is responsible for the overall rural road development, including the maintenance, rehabilitation, and upgrade of those roads. Over the last decade, MRD has devoted millions of budgets and mobilized several large investment projects from the development partners to improve the rural road conditions, including paving over 4,300 km rural roads as of 2022. The budget allocated for rural road maintenance has also been steadily increasing, reaching USD 25 million in 2021. Nevertheless, about 90 percent of rural roads remain unpaved and undrained, making rural accessibility an acute challenge during rainy reasons spanning between May and September each year. The backlog of maintenance also remains an acute challenge.

Table 1: Rural Road Network in Cambodia

Paved and Unpaved	Surface Type	Length (km)	Share
Paved Rural Roads	Single Bituminous Surface Treatment	408	9.17%
	Double Bituminous Surface Treatment	3,166	
	Reinforced Concrete	821	
	Sub-total	4,396	
Unpaved Rural Roads	Laterite or Earth	43,523	90.83%
	Total	47,919	100%

Source: MRD, 2022

2.2. Climate Risk Exposure and Implications for Prioritization

Climate change puts further stress to Cambodia's rural roads. With around 85 percent of the country territory, including most of its populated areas, located within the Mekong River and Tonle Sap basins, Cambodia is highly vulnerable to extreme climatic hazards, particularly river floods. Increasingly more frequent and intense, extreme floods cause significant direct damages to Cambodia's rural roads and indirect economic damage from the loss of connectivity and logistic services. In October 2020, consecutive extreme rainfalls led to an estimated 80-year flood that disrupted more than 1400km of rural roads across the province of Pursat, Battambang, and Banteay Meahnchey. Eighteen rural bridges were flooded[1].

Looking ahead, climate change projections indicate temperature increase of 0.7°C–2.7°C by 2060 and increased intensity and frequency of extreme precipitation in the monsoon season and flooding (World Bank undated) which would only exacerbate current vulnerabilities.

In response to the climate change risks, MRD puts a high priority to build climate resilience across the rural road network. In MRD's Rural Road Policy for 2020-2030, it aims to connect all communes as well as 75 percent of all villages by all-season roads, providing access to at least 9.8 million rural people by 2030. Nevertheless, with limited fiscal resources as many other road authorities in developing countries struggles, MRD needs to prioritize its investment effectively to optimize the result.

The challenge of prioritizing investment is that each rural road serves multiple purposes for human and socio-economic development. Some link to schools to enable children to receive education (Vasconcellos 1997); some link to health and medical centers and enable people to receive treatments that sometimes save lives (Gage and Calixte 2006); some link to employment base such as factories, farmlands, and commercial centers and enable people to reach job opportunities for their livelihoods (Hallegatte, Rentschler, and Rozenberg 2019); some enable agricultural and

[1] World Bank, 2021, Rapid Assessment of 2020 floods in selected regions in Cambodia

processed foods to reach their markets to ensure food supply for consumers (Limi, You, and Wood-Sichra 2017).

On top of that, different rural road sections vary in terms of their relative vulnerability to climate change risks. Roads that are close to rivers or lakes or located within the watershed are typically more exposed to flood risks. Roads with poor conditions or insufficient engineering designs have a higher level of physical fragility when climatic shocks occur. In addition, the negative socio-economic impact associated with flood-induced disruption also vary across different rural road sections, depending on the role they play in providing access for nearby communities and in feeding freight flows into the wider logistic networks and corridors for domestic consumption and international trade.

Decision-makers need to take into account of all these indicators and be able to compare the relative criticality of each road when investing in rural road infrastructure. Given the localized nature of climate risks, a spatially targeted approach in identifying the most vulnerable road sections is sensible. Adding climate vulnerability analysis onto the rural road criticality analysis through geo-spatial assessment offers promising opportunity for a risk-informed investment prioritization at rural road authority.

3. A Prioritization Framework for Resilient Rural Road Planning

This report introduces an innovative framework to assist MRD prioritizing its investment and interventions for rural roads at commune level. The framework takes into account both the criticality of roads in terms poverty reduction, human development, and logistic supply, and the climate vulnerability of roads in terms of the negative impact of connectivity loss due to flood disruptions.

3.1. The Proposed Framework

The proposed framework entails a two-step method to prioritize rural road improvement interventions:

1. Prioritize the communes of intervention based on a country-wide multicriteria analysis.
2. Within the shortlisted communes, select roads based on a context-specific assessment.

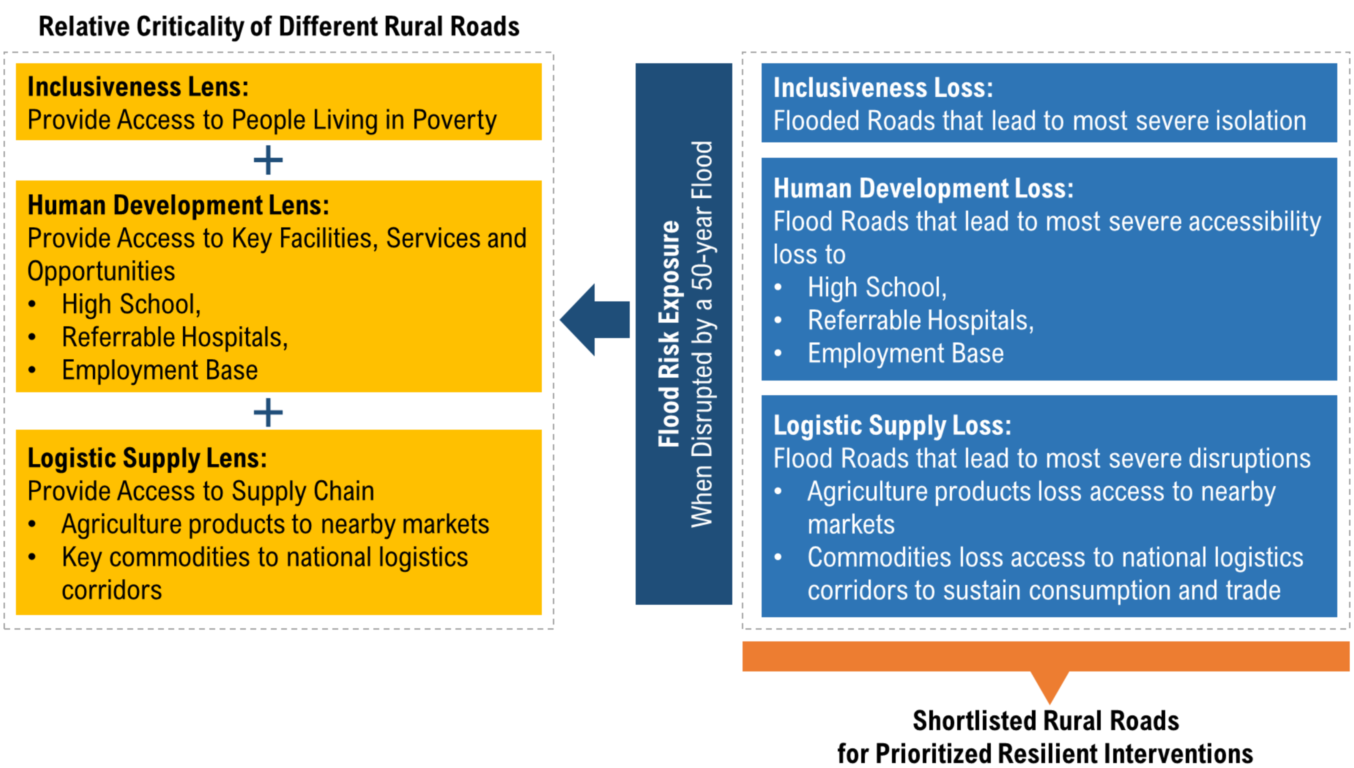
Communes are the third administrative layer after provinces and districts. There are over 1,600 communes in Cambodia. Their average area is 110 km^2, and they contain, on average, 32 km of roads. Such a detailed resolution will facilitate the identification of specific rural roads for improvement. The prioritization of communes integrates three development lenses with a total of six indicators to quantify the overall relative criticality of rural roads at commune level. The three-development lens are **(i) Inclusiveness, (ii) Human Development,** and **(iii) Logistic Supply**.

The **'Inclusiveness'** lens is measured by an indicator focusing on poverty reduction. It evaluates the size of rural population living in poverty in a commune. This larger the population size living in poverty, the more critical roads in this commune are, which connect this commune with the rest of the country.

The **'Human Development'** lens is measured by three indicators focusing on rural accessibility for human development. It evaluates the relative importance of rural roads in a commune in providing access for rural communities (i) to reach schools for education, (ii) to reach hospitals for medical services, and (iii) to reach employment base for job opportunities. The relative importance of rural roads under this lens is represented by the percentage of rural population that loses accessibility to these facilities and opportunities when the road is disrupted by flood.

The **'Logistic Supply'** lens is measured by two indicators focusing on the flow of products and commodities via rural roads of a commune. It evaluates the relative importance of rural roads (i) in providing access for local agriculture products to reach the nearby market in a timely manner, and (ii) in feeding the critical commodities into logistical corridors for domestic household and industrial consumption across Cambodia and for Cambodia's international trade. The relative importance of rural roads under this lens is represented by the value of agriculture products that loses accessibility to markets when a 50-year flood occur (for indicator (i)), and the indirect supply-chain impacts for consumers triggered by the flooding of the communes' rural roads.

Figure 1:Prioritization Framework for Resilient Rural Roads



All these six indicators across three development lenses together define the relative criticality and climate vulnerability of rural roads in a commune. Rural roads in communes with the highest criticality and climate vulnerability should be prioritized for investment and interventions. Figure 1 illustrate the overall logic of the proposed prioritization framework.

3.2. How the Prioritization Framework is Applied

The relative importance of a commune within each indicator is calculated by two geospatial models (see next section) based on the definitions provided in the previous section. For each indicator, the models generate a quantitative result X_i for each commune *i*, e.g., the percentage of population that loses accessibility to schools when flooded, which is turned into a score S_i on a 0-to-100 scale, as follows: $S_i = (X_{max} – X_i) / (X_{max} – X_{min})$. Those scores S_i, called **Road Criticality Score,** are objective and represent the relative importance of rural roads at commune level in terms of inclusiveness, human development, and logistic supply.

When decision makers apply the framework, they would assign another **Adjustable Weight** on a 0-to-5 scale for each of the six indicators across three development lenses. The specific weight assigned to each indicator should reflect their relative priority level from the decision-makers' perspective as a result of consultations with involved communities. The adjustable weight system allows the policymakers to consult and adjust the relative priority level of each indicator in line with real-life situations, such as political preferences. These metrics may also show complementarities or trade-offs that will feed into the policy discussion and inform better planning.

Table 2: Illustrative Example of Generating Rural Road's Prioritization Score

Commune ID	Development Lens	Indicators		Road Criticality Score	Adjustable Weight	Prioritization Score
				0-100, Model Generated	0-5, Decision-maker Assigned	Weighted Average
C0001	Inclusiveness	1	The size of rural population living in poverty that a rural road serves	10	3	20.16
	Human Development	2	The percentage of rural population that loses accessibility to schools when flooded	30	2	
		3	The percentage of rural population that loses accessibility to hospitals when flooded	10	5	
		4	The percentage of rural population that loses accessibility to employment base when flooded	50	1	
	Logistic Supply	5	The value of agriculture products that loses accessibility to markets when flooded	20	5	
		6	The increase in product price or loss of product availability due to the disruptions of supply chains by flood	40	3	

Lastly, the model-generated Road Criticality Scores to each commune and the decision-maker assigned Adjustable Weight to each indicator are multiplied into a single score – the **Prioritization**

Score. This Prioritization Score for each commune then represent its places in the priority ranking for investment and interventions. The higher the score, the higher the need for interventions for rural roads in this commune. Table 2 illustrates how the Prioritization Score is calculated based on the Road Criticality Score and the Adjustable Weight.

The relative vulnerability and criticality level of communes are calculated for all 1,600 Cambodian communes, which on average covering an area of about 110 km^2 and containing 32 km of roads. Such a detailed resolution can help relevant stakeholders prioritize investments by identifying rural roads at commune level for which resilient interventions would lead to multi-front benefits across six human and socio-economic development indicators.

4. Underpinning Geospatial Models

Generating the Road Criticality Score is a key part for applying the proposed prioritization framework. The Road Criticality Score is calculated for each commune by calibrating results from two underpinning geospatial models, namely the Resilient Accessibility Model and the Logistic Supply Model.

4.1. Core Data

Both models are based on the same geospatial units, the villages or *phum* in Khmer, which are the fourth administrative entity in Cambodia after provinces or *khaet*, districts or *srok*, and communes or *khum*. The geographic coordinates of about 14,000 villages were provided by MRD. These data were updated to reflect changes in administrative boundaries that occurred between 2008 and 2021.

Using the most recent data available for Cambodia, villages are assigned with a value of:

3. **Population**, based on the 2019 Cambodia Population Census,
4. **Poverty level**, based on the 2021 Cambodia Household Survey,
5. **Logistic commodity data**, based on 2011 Cambodia Business Census and 2015 UN CommTrade data,
6. **Livestock and crop production**, based on the 2010 results of the Spatial Production Allocation Model of the International Food Policy Research Institute,
7. **Fishing and logging activities**, based on the 2015 fishing intensity estimates from Halpern et al. (2015) and on the 2016 forest cover changes estimates from Hansen et al. (2016),
8. **The number of workers** in 60 divisions of the Nomenclature of Economic Activities, based on the 2011 Cambodia Business Census.

Both models also rely on the same road network data taken from MRD (2021) and Open Street Map (2019). The accessibility model uses all types of rural roads, totaling over 47,000 km of roads. The supply chain only considers primary, secondary, tertiary, and the main rural roads, totaling about 15,500 km of roads.

4.2. Resilient Accessibility Model

The Resilient Accessibility Model covers five out of six indicators in the prioritization framework. The Resilient Accessibility Model used for the proposed prioritization framework is built on a previous model developed by Espinet Alegre et al. (2020). Most of the modelling methods, assumptions, and analytical approach used by Espinet Alegre et al. are kept in the Resilient Accessibility Model of this study, which is described later.

Table 3: Development Lens and Indicators under the Resilient Accessibility Model

Development Lens	Indicator
Inclusiveness	1. The size of rural population living in poverty that a rural road serves
Human Development	2. The percentage of rural population that loses accessibility to schools when flooded. 3. The percentage of rural population that loses accessibility to hospitals when flooded. 4. The percentage of rural population that loses accessibility to employment base when flooded
Logistic Supply	5. The value of agriculture products that loses accessibility to markets when flooded

Compared with the model developed by Espinet Alegre et al., the Resilient Accessibility Model introduces several additional features. Firstly, the geographic coverage of the Resilient Accessibility Model expands from three provinces under Espinet Alegre et al. (Kratie, Tboung Khmum, and Kampong Cham) to the entire country of Cambodia. Secondly, it added an indicator on inclusiveness by geospatially linking rural road accessibility with poverty levels across Cambodian communes. By doing so, it brings to light the relative importance of rural roads to keep the poorest connected to the rest of the country. Thirdly, it introduced an indicator to evaluate the number of jobs reachable by a community via certain rural roads within a 60-minute journey. It forms a proxy to measure the easiness for rural workforce to access jobs, and how such access could be negatively affected by floods when those roads are not upgraded with climate resilient interventions.

The following sections describe how each of the five indicators are modelled.

Development Lens	Indicator
Inclusiveness	1. The size of rural population living in poverty that a rural road serves

Adding the latest household income census in 2021, this study puts the relative importance of different roads for poverty reduction into the equation. The census data allows the study to identify rural roads that serve the communities with highest poverty rate in Cambodia. Those roads hence are allocated with higher criticality level due to their irreplaceable role for inclusive development.

Development Lens	Indicator
Human Development	2. The percentage of rural population that loses accessibility to schools when flooded. 3. The percentage of rural population that loses accessibility to hospitals when flooded. 4. The percentage of rural population that loses accessibility to employment base when flooded
Logistic Supply	5. The value of agriculture products that loses accessibility to markets when flooded

The accessibility model is similar to that of Espinet Allegre et al. (2020); see this paper for technical details[2]. The main features of the model and the innovations under this study compared to that of Espinet Allegre et al. (2020) are succinctly presented in this section.

Using geospatial data, the model evaluates the rural accessibility by calculating the shortest travel time between a village and the closest Points of Interests (PoI), which include schools, hospitals, markets, and firms. The geographic coordinates of hospitals, schools, and markets were given by the Cambodian Ministries of Health, Education (MHE), and MRD, or extracted from Open Street Maps (2019) and validated by MRD. Data on locations of firms comes from the 2011 Cambodia Business Census. It indicates the villages where registered firms are located as the employment base and their number of workers.

The model measures accessibility as the ability of rural people or agricultural products to reach hospitals, schools, employment base, or regional markets in a given time frame. Three travel modes are modelled: bicycle, vehicle, and ferry boats. Walking up to 2km is also modelled as last-mile connectivity in addition to the main modes of transportation. The model assumes that people have unrestricted access to road vehicles, to established river-crossing ferry boats, and can walk off-road on land.

The model also simulates the change of accessibility in the effect of flooding. It assumes that roads become impossible to use with more than 0.5m of water above road design levels for vehicles and 0.25m for bicycles. Walking becomes impossible for any road under the flood zone regardless of water depths. The model does not consider specific design or location of bridges or culverts. Rather, it assumes that a water depth equal to or less than the hydraulic design would not damage the road accessibility.

Table 4: Road Network Characteristics and Assumptions

Road Type	MRD Classification	Speed by Modes (km/hour)	Hydraulic Design Return Period (years)
Primary	T1	60	25
Secondary	T2	40	25
Tertiary	T3	20	10
Rural roads (vehicles)	T4	10	-
Rural roads (bicycles)	T4	10	-
Walking	-	4	-
Ferry Boards (river crossing)	-	3	-

The road design standard used by MRD date back to early 2000-2003. The design standards are based on current catchment areas and historical rainfall data. These standards detail the classification of the roads and the geometric design indicators by road class - Rural Road Tier 1,

[2] Espinet Allegre et al. (2020) 'Analyzing Flooding Impacts on Rural Access to Hospitals and Other Critical Services in Rural Cambodia Using Geo-Spatial Information and Network Analysis', World Bank Policy Research Working Paper 9262.

Tier 2, Tier 3, and Tier 4. MRD standards includes little information with regard to hydraulic design and no details on design requirements for specific road protection elements, as scour protection, retaining walls, slope stabilization or flood protection of the pavement. The assumptions for travel speed and road design standards are summarized in the table below. These assumptions were validated by MRD.

The Resilient Accessibility Model has the following main steps:

Step 1: Simulating Baseline Accessibility:

1. The travel time to the closest point of interest (schools, hospitals, employment base, or markets) is calculated for each cell in the project area.[3] The cell resolution is 500 m.
2. The population and value of agricultural production are aggregated at the 500 m resolution.
3. The population and value of agricultural production are combined with travel time and aggregated for three accessibility thresholds – 30 minutes, 60 minutes, and over 60 minutes. In some instances, some population or agriculture cells may not have road access to a certain point of interest. those populations are considered 'isolated' and would be counted as such.

Step 2: Simulating Accessibility Change under a 50-year Flood

4. Intersect floods map with road network. Flood event model is a 50-year return event.
5. Disrupt road network based on hydraulic designs. For example, a main road will be disrupted if the depth difference between the 50-year flood and the 20-year flood is more than 0.5 m. This is calculated for each segment based on the design assumption.
6. Recalculate travel times and value of agricultural products for each cell based on this flood-disrupted scenario.
7. Compare baseline with flood-disrupted scenarios and calculate increased travel time and decreased value of agricultural products (or loss of access) for non-isolated cells. Identify increased isolated cells due to flooding.

Step 3: Calculating and Ranking the Absolute Loss of Accessibility of Road Segments

8. Combine loss of access respective to schools, hospitals, and employment base by population size, and the value of agricultural products losing access to markets to derive the absolute loss of accessibility for each road segment.
9. Normalize the value of each road segment's absolute loss of accessibility from 0 to 100.
10. Rank road segments by their value of absolute loss of accessibility from high to low.

Flood maps for return periods of 5, 10, 20, and 50 years were provided by Deltares. They are derived from so-called global digital elevation models (DEM) and have a resolution of 30 meters by 30 meters. The mean limitations of the Deltares flood maps include that (a) they only cover

[3] Note: In rural context, density of critical facilities is very low, and the population normally has only one choice based on distance, as it is the case in the pilot provinces. In urban context, this assumption may not be valid as people's choices for critical facilities may depend on a wide range of factors (e.g., facility reputation, insurance, social network, etc.).

riverine floods, and (b) they reflect only the historical flood levels and do not integrate climate change projections for the future.

The passability of roads for vehicles and pedestrians during a flood depend on the several key factors, namely (i) flood depth levels, (ii) land terrain, and (iii) the road conditions and engineering characteristics. Flood depth levels are derived from flood depth maps issued by Deltares. In terms of land terrain, the model assumes a flat terrain for all cells given that Cambodia is mainly located on plains of the Mekong River and Tonle Sap basins. The road conditions and engineering characteristics follow the assumption presented in Table 4.

Note that the Employment Opportunities Access indicator is calculated at the commune level and not at the village level for computation purposes. Specifically, jobs are attached to the largest village of a commune. In terms of employment bases such as factories or large agriculture processing facilities, their locations are much sparser from communes compared to schools, hospitals, and markets. Therefore, the accessibility to job opportunities is measured by number of jobs reachable within one hour from the largest village of a commune are counted for that commune.

4.3. Logistic Supply Model

Road disruptions have tremendous economic impacts because they perturb trade and supply chains (Hallegatte, Rentschler, and Rozenberg 2019, Rozenberg et al. 2019). The Logistic Supply Model simulates how the flow of Cambodia's key economic products gets rerouted or blocked when some roads are closed as a result of a shock, in this case, flooding. It estimates the cascading impacts of such disruption along supply chains and on Cambodian households and international trade (Figure 2).

Figure 2: Shock Pathways across the Logistic Supply Chain

Under this model, the relative climate vulnerability of each road segments in Cambodia's logistic supply chain is quantified by the increase of product prices and the loss of product availability when such road segment is disrupted. For each road segment, this criticality score is multiplied by the length of the road. To calculate the commune-level **Logistic Supply Score**, we sum for each commune the weighted criticality scores of MRD roads only, then turn the result into a 0-to-100 number.

Table 5: Development Lens and Indicators under the Logistic Supply Model

Development Lens	Indicator
Logistic Supply	6. The increase in product price or loss of product availability due to the disruptions of supply chains by flood

The model is similar to Colon, Hallegatte, and Rozenberg (2021); see this paper for technical details[4]. The main features of the model and main innovations introduced by this study compared to Colon, Hallegatte, and Rozenberg (2021) are succinctly presented below.

This model is built on various high-resolution data from which the agents are modeled: Cambodian households, Cambodian firms, and trading countries. In the model, Cambodia's economy is represented by 721 representative households and 1,181 production units from 13 sectors located on 721 of the most economically significant communes. This modeling is based on the 2011 Cambodia Business Census (which includes business data for sectors such as garment, textile, manufacturing etc.) and 2019 Cambodia Population Census, complemented by sector-specific data on agriculture, fishing, and forestry.

Cambodia's logistic supply chain is reconstructed by the model to link suppliers and buyers among firms and trading countries. This is done via a probabilistic gravity-based model, which assumes that large logistic flows occur between large firms close to one another. Production processes, i.e., the inputs need for each sector, are derived from the 2015 national input-output table. Cambodian supply chains are then connected to relevant trading countries using the 2015 UN CommTrade data.

The flows of goods in these domestic and international supply chains are mapped onto the Cambodia's transport network, which consists of roads, railways (270 km), and waterways (1,200 km). The primary international transit points are the Sihanoukville seaport and Phnom Penh inland river ports and the terrestrial borders of Bavet and Poipet. Note that the road network used by the Logistic Supply Model is different from the Resilient Accessibility Model. Unlike the Resilient Accessibility Model where all road in Cambodia is used, the road network used here only includes about 15,000 km national, provincial, and major rural roads that are of logistic importance in Cambodia.

For transportation speeds and costs, the model uses values that were primarily derived from data collected by the Japan International Cooperation Agency (JICA, 2016) and tailored to freight transportation.

The main assumptions for the modeling of supply-chain reactions to disruptions are the following.

- In normal times, suppliers provide their intermediate goods to other firms using the least-cost path on the road network. This journey is associated with a transport cost that is paid for by the client.
- Following the disruption of a route, if there is an alternative, more expensive path, the increase in transport cost is transferred to the client.
- If no alternative route exists, or if it is more than twice more expensive as the normal one, then no good will be delivered, causing production or welfare losses.
- If suppliers fail to deliver for too long, inventories will get exhausted, causing production delays or losses.

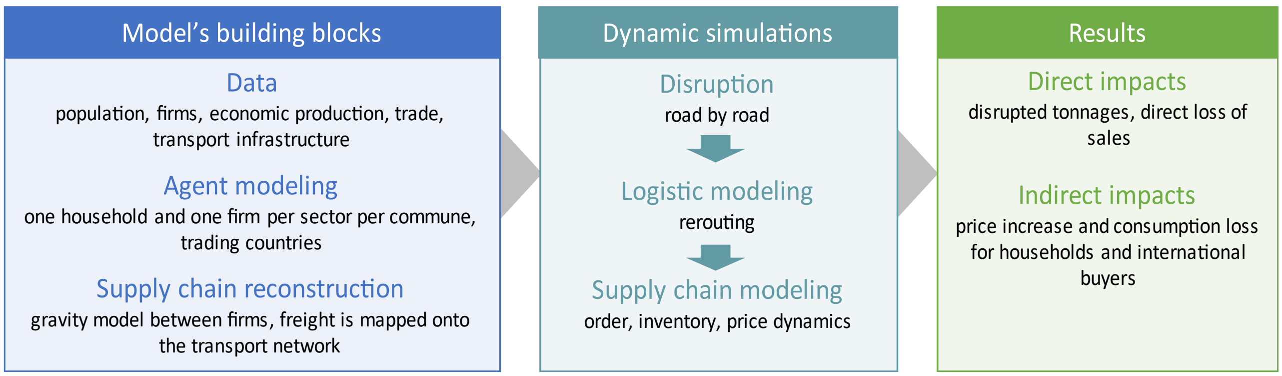
For each road disruption, the model simulates how freight flows are rerouted on the transport network and the induced reactions in the supply chains following the assumptions listed above.

Using logistics and inventory dynamics, the Logistic Supply Model has the following main steps:

[4] Colon, C., Hallegatte, S., and Rozenberg, J. (2021), A transport—supply-chains agent-based model to inform risk management.

1. Simulate a one-week disruption of an MRD-managed road segment (by flooding in this study).
2. Determine how supply-chain flows get rerouted or blocked.
3. Calculate the impact on prices and product availability.
4. Assess the final cost for households and trade partners.

Figure 3: Main Features of the Supply Chain Model



Source: Colon, Hallegatte, and Rozenberg (2021)

The model simulates the disruption of each transport infrastructure asset, one by one, and show the resulting economic impacts on the transport map. When all supply chains are considered, these criticality maps show the relative criticality of each transport infrastructure for the overall economy (including the producers and consumers located in different regions).

The list of indicators used for the Logistic Supply Model is given in Appendix A. The code of the model is available on this public repository: https://doi.org/10.5281/zenodo.7427207.

5. Revealing the Climate Vulnerability of Rural Roads

The geospatial analysis embedded in the model provides a powerful insight to reveal the impact of climate change and flood risks to rural inclusiveness, human development, and logistic supply. This section presents a vulnerability assessment of Cambodia's communes to flood-induced rural road disruption using the geo-spatial modelling results.

5.1. Baseline Accessibility Results

Table 6 shows the results of the baseline rural accessibility level in the absence of flood. About 70 percent of the Cambodian rural population have road access to a referral hospital within 60 minutes, and almost two-thirds have road access to a high school within 30 minutes. Note that road access to high schools and jobs considers the whole population regardless of age. Over two-thirds of agricultural products can be transported to a market within 60 minutes.

Table 6: Results – Accessibility Baseline Scenario (without Flood, Dry Season)

Travel Time	Percentage of people with access to referral hospitals	Percentage of people with access to high schools	Percentage of value agricultural production with access to markets
0–30 minutes	48.2%	64.4%	27.6%
30–60 minutes	22.9%	20.3%	27.9%
More than 60 minutes	27.6%	14.1%	43.8%
No access	1.3%	1.2%	0.8%

In terms of employment bases such as factories or large agriculture processing facilities, their locations are much sparser from communes compared to schools, hospitals, and markets. Therefore, the accessibility to job opportunities is measured by number of jobs reachable within one hour from communes. It is estimated that each Cambodian has access to about 118,000 jobs within an hour. Within 60 minutes, they can reach as many jobs as there are in each province.

These results vary significantly among provinces, which underline accessibility gaps. The provinces with the best accessibility contain urban centers, such as Phnom Penh and neighboring Kandal, Battambang, Siem Reap, and Banteay Meanchey. Kep and Takeo, two Southern provinces, also stand as highly accessible provinces. On the other hand, the North and Northeast rural provinces rank low in the baseline rural accessibility, namely Oddar Meanchey, Preah Vihear, Stung Treng, Rattanakkiri, and Mondulkiri. Svay Rieng, in the Southeast, also exhibits a low level of accessibility.

Some uneven performance between accessibility indicators is observed. There is a positive correlation between access to high schools and referral hospitals, i.e., when there is good access to high schools, there tends to be good access to referral hospitals and vice versa. One noticeable exemption is the small province of Pailin, in the West of the country. Access to high school is good, with 83 percent of the population having access to a high school within 30 minutes, but access to referral hospitals is very poor. All the population needs more than an hour to reach a hospital.

People's accessibility to hospitals also positively correlates with farms' accessibility to markets, but to a lower extent. Preah Sihanouk lies outside this correlated trend. Accessibility to referral hospitals and high schools is high, but farms have poor access to markets, with only 7 percent of the value of farm production able to reach a market within 60 minutes.

Finally, employment opportunities are enormously concentrated in Phnom Penh and neighboring Kandal. Besides those urban provinces, there is a positive correlation between employment opportunities and the other accessibility indicators. Kampong Speu stands out as an outlier. Due to the vicinity of the Phnom Penh area, accessibility to jobs is well above average, whereas accessibility to high schools and referral hospitals is below average.

Population density strongly correlates with employment opportunities. Jobs and economic activities grow considerably with density. But it should be noted that density does not necessarily determine accessibility to essential facilities. For instance, Koh Kong and Kratie are very sparsely populated, but accessibility to referral hospitals is above average. Prey Veng is relatively densely populated, but accessibility to high schools and referral hospitals is below average.

Table 7: Results – Baseline Accessibility Scenario

Province code and province name	Population	Percentage of people with access to referral hospitals < 60 min	Percentage of people with access to high schools < 30 min	Percentage of the value of agri-products with access to markets < 60 min	Number of jobs accessible < 60 minutes
1. Banteay Meanchey	861,883	76%	63%	65%	23,856
2. Battambang	997,169	73%	65%	79%	38,781
3. Kampong Cham	899,791	70%	63%	37%	35,407
4. Kampong Chhnang	527,027	57%	52%	45%	25,555
5. Kampong Speu	877,523	64%	51%	62%	110,554
6. Kampong Thom	681,549	62%	56%	56%	16,909
7. Kampot	593,829	67%	55%	62%	11,657
8. Kandal	1,201,581	87%	79%	65%	342,707
9. Koh Kong	125,902	63%	59%	12%	2,587
10. Kratié	374,755	61%	47%	22%	17,820
11. Mondulkiri	92,213	37%	33%	1%	863
12. Phnom Penh	2,281,377	96%	95%	95%	526,852
13. Preah Vihear	254,827	31%	49%	1%	8,763
14. Prey Veng	1,057,720	60%	47%	59%	25,648
15. Pursat	419,952	60%	58%	80%	12,298
16. Ratanak Kiri	217,453	45%	36%	26%	3,958
17. Siem Reap	1,014,234	75%	64%	79%	43,485
18. Preah Sihanouk	310,072	88%	87%	7%	41,744
19. Stung Treng	165,713	41%	38%	0%	2,903
20. Svay Rieng	525,497	49%	49%	39%	16,091
21. Takéo	900,914	76%	70%	51%	71,009
22. Oddar Meanchey	276,038	52%	43%	31%	3,843
23. Kep	42,665	97%	83%	100%	21,761
24. Pailin	75,112	0%	84%	87%	12,949
25. Tboung Khmum	776,841	64%	50%	53%	23,167

5.2. Flood Impact to Accessibility

Table 7 shows the recalculated accessibility results when Cambodia experiences a 50-year flood. For the three indicators, a sharp increase in the number of people who cannot reach the desired facility (+13% vs. the baseline) is observed, either because they live in a flooded area or because all routes could take to reach their destination are flooded. The impact of floods is more substantial on health than on education and farm-to-market accessibility. About 15 percent of Cambodians lose access to a hospital within 60 minutes, vs. 11 percent for high schools and farm-to-market accessibility during flooding. The number of jobs accessible within 60 minutes to Cambodians is reduced by 28 percent, from 118,000 to 86,000 during flooding. Within 60 minutes, they can reach 85 percent of the jobs in the province where they live (-15 percent vs. the baseline).

Table 8: Results – Accessibility Under Floods

Travel Time	Percentage of people with access to referral hospitals (Change vs. baseline)	Percentage of people with access to high schools (Change vs. baseline)	Percentage of the value of agricultural production with access to markets (Change vs. baseline)
0–30 minutes	38.4% (-9.8%)	56.2% (-8.3%)	21.4% (-6.2%)
30–60 minutes	18.2% (-4.7%)	17.6% (-2.7%)	23.1% (-4.8%)
More than 60 minutes	29.4% (+1.8%)	12.8% (-1.2%)	39.1% (-4.7%)
No access	14.0% (+12.8%)	13.4% (+12.2%)	16.5% (+15.7%)

Accessibility is very differently affected depending on the provinces; see Table 9. Most impacts are located in Battambang and Prey Veng, the third and fifth most populated provinces. In Battambang, almost half of the people - about 478,000 - loses access to a hospital within 60 minutes, and 20 percent lose access to high schools within 30 minutes. Access to job opportunities is also reduced by half. These results highlight a dire need to improve the resilience of road accessibility to those facilities and employment base that can withstand floods in this province. In Prey Veng, nearly 60 percent of job opportunities are unreachable during the flood, and 30 percent of the farm products fail to reach a market in 60 minutes. These results highlight that the economic activities of this province are highly dependent on a few but floodable roads.

Other significantly affected provinces are Banteay Meanchey, Kampong Thom, Kandal, and Kampong Cham. Accessibility in Pursat and Stung Treng is also strongly affected, although their population size is small. Phnom Penh appears to be less vulnerable to floods than other provinces, but because it concentrates 15 percent of the country's population, the impacts of floods would still be sizeable.

The impact on one indicator often strongly positively correlates with the impacts on the other indicators. Note that floods have almost always a more significant impact on hospital accessibility than on high school accessibility. Half of the provinces exhibit almost no effect on farm-to-market accessibility. The decrease in employment opportunities can be very severe. In six provinces, floods make most jobs unreachable.

Table 9: Results – Change in Accessibility Under Floods

Province code and province name	Population	Percentage of people losing access to referral hospitals within 60 min	Percentage of people losing access to high schools within 30 min	Percentage of the value of agricultural production losing access to markets within 60 min	Relative change in the number of jobs accessible within 60 minutes
1. Banteay Meanchey	861,883	-24.9%	-11.3%	-17.0%	-41.2%
2. Battambang	997,169	-47.9%	-21.3%	-21.4%	-43.6%
3. Kampong Cham	899,791	-18.3%	-19.9%	-16.9%	-71.2%
4. Kampong Chhnang	527,027	-7.9%	-8.7%	-3.2%	-30.8%
5. Kampong Speu	877,523	-1.2%	0.0%	0.0%	-19.1%
6. Kampong Thom	681,549	-23.4%	-13.4%	-17.1%	-35.1%
7. Kampot	593,829	0.0%	-0.9%	-0.1%	-11.1%
8. Kandal	1,201,581	-16.8%	-8.5%	-13.7%	-48.8%
9. Koh Kong	125,902	-12.7%	-11.5%	0.0%	-30.4%
10. Kratié	374,755	-16.3%	-8.0%	-1.6%	-12.5%
11. Mondulkiri	92,213	-5.1%	-3.2%	0.0%	-10.7%
12. Phnom Penh	2,281,377	-7.0%	-2.8%	-11.8%	-18.8%
13. Preah Vihear	254,827	-6.2%	-1.8%	0.0%	-11.2%
14. Prey Veng	1,057,720	-33.9%	-19.6%	-29.4%	-59.5%
15. Pursat	419,952	-21.1%	-17.9%	-20.1%	-52.5%
16. Ratanak Kiri	217,453	0.0%	-1.8%	-0.4%	-23.2%
17. Siem Reap	1,014,234	-7.3%	-4.7%	-8.4%	-9.4%
18. Preah Sihanouk	310,072	-10.7%	-3.5%	-0.5%	-16.9%
19. Stung Treng	165,713	-20.1%	-18.2%	0.0%	-60.4%
20. Svay Rieng	525,497	0.0%	0.0%	-2.2%	-10.5%
21. Takéo	900,914	-13.2%	-5.4%	-6.4%	-20.0%
22. Oddar Meanchey	276,038	-1.0%	-2.4%	-1.2%	-5.7%
23. Kep	42,665	-5.5%	0.0%	0.0%	0.0%
24. Pailin	75,112	0.0%	-5.4%	-6.4%	0.0%
25. Tboung Khmum	776,841	-3%	-1%	0%	-28.7%

5.3. Interventions to Improve Accessibility Resilience

To gauge the opportunities for road investment in the different provinces of Cambodia, we designed three intervention scenarios: the improvement of bridges, road drainage, and or road drainage and surface. A 50-year flood is simulated with these improvements, and the accessibility indicators are recalculated, see table 11.

Table 10: Results – Improved Accessibility Under Floods with Certain Interventions

Scenario	Percentage of people who do not lose access to hospitals within 60 min thanks to road improvements	Percentage of people who do not lose access to high schools within 30 min thanks to road improvements	Percentage of agricultural production that can still be transported to a market within 60 min thanks to road improvements
Improved bridges only	+0.6%	+0.2%	0%
Improved drainage only	+3.2%	+1.4%	+1.2%
Improved drainage and surface	+3.7%	+2.1%	+2.3%

Improving drainage has a powerful impact on public health, with 3.2 percent of the people at the national level regaining access to hospitals within 60 minutes. In other words, thanks to improved drainage, the number of people unable to access hospitals within 60 min goes down from 14.5 percent to 11.3 percent, i.e., the impact of floods is reduced by 22 percent. This measure reduces the impact of floods on high school accessibility by 16 percent and by 11 percent on farm-to-market accessibility. Improving bridges by itself only has a limited effect on accessibility. Improving surface on top of drainage has a limited potential to markedly improve hospital accessibility, whereas it does have a substantial impact on high school and farm-to-market accessibility.

Table 11 shows the results for seven provinces, namely Battambang, Prey Veng, Banteay Meanchey, Kampong Thom, Kandal, Pursat, and Stung Treng, for the scenario with improved drainage. These provinces are the most vulnerable to flood with regard to their accessibility.

Interventions are likely to substantially improve the resilience of road accessibility to floods in Battambang. The alleviation of food impact on hospital access is particularly remarkable, with 32 percent of the residents of Battambang regaining access to a hospital within 60 minutes. Interventions may also be desirable for Banteay Meanchey, which exhibits a sizeable recovery of road access to hospitals, high schools, and farm-to-market accessibility. Although Prey Veng is particularly vulnerable to floods, improving drainage would not improve road accessibility during a 50-year flood. This finding indicates that such flood would be so intense in this province that the improvement of drainage—as modeled here, i.e., an improvement of hydraulic design such that the road can remain unflooded during a 20-year flood—would have very limited effect.

Table 11: Results – Benefits of Improved Drainage for Seven Provinces

Province code and province name	Population	Percentage of people who do not lose access to hospitals within 60 min due to improved drainage	Percentage of people who do not lose access to high schools within 30 min due to improved drainage	Percentage of agricultural production that can still be transported to a market within 60 min due to improved drainage
1. Banteay Meanchey	861,883	9.5%	3.5%	9.3%
2. Battambang	997,169	32.1%	8.3%	5.5%
6. Kampong Thom	681,549	4.2%	3.7%	3.0%
8. Kandal	1,201,581	0.2%	0.1%	0.0%
14. Prey Veng	1,057,720	0.0%	0.0%	0.0%
15. Pursat	419,952	2.2%	1.4%	1.1%
19. Stung Treng	165,713	0.0%	1.8%	0.0%

6. Application Illustration for Rural Road Prioritization

This section illustrates the application of the proposed prioritization framework, using result generated from the underpinning geospatial models. This illustration aims to provide a concrete example to decision-makers at MRD and beyond on the practicality and usefulness of this framework in assisting prioritizing investment for rural roads at commune level.

The proposed a two-step method to prioritize interventions for rural road includes:

1. Prioritize the communes of intervention based on a country-wide multicriteria analysis.
2. Within the shortlisted communes, select roads based on a context-specific assessment.

This illustration performs step 1, i.e., the prioritization of communes. Communes are the third administrative layer after provinces and districts. There are over 1,600 communes in Cambodia. Their average area is 110 km^2, and they contain, on average, 32 km of roads. Such a detailed resolution will facilitate the identification of roads. The full realization of step 2 goes beyond the scope of this report. It should be performed by surveying road conditions and identify location specific resilience engineering interventions required.

Note that the priority list presented in this report is very much dependent on the decision-making indicators of the multicriteria analysis, i.e., the indicators included, their definition, and the weights used to aggregate them. Before feeding such a list to real decisions, those indicators need to be carefully reassessed and further aligned with MRD's objectives.

For illustration, all six indicators across three development lenses are assigned with the same Adjustable Weight as '1'. The results presented therefore reflect the model generated prioritization level based on the Road Criticality Score.

Table 12: Illustrative Example of Generating Rural Road's Prioritization Score

Commune ID	Development Lens	Indicators		Road Criticality Score	Adjustable Weight	Prioritization Score
				0-100, Model Generated	0-5, Decision-maker Assigned	Weighted Average
C0001	Inclusiveness	1	The size of rural population living in poverty that a rural road serves	10	1	26.66
	Human Development	2	The percentage of rural population that loses accessibility to schools when flooded	30	1	
		3	The percentage of rural population that loses accessibility to hospitals when flooded	10	1	
		4	The percentage of rural population that loses accessibility to employment base when flooded	50	1	
	Logistic Supply	5	The value of agriculture products that loses accessibility to markets when flooded	20	1	
		6	The increase in product price or loss of product availability due to the disruptions of supply chains by flood	40	1	

Table 12 shows the relative priority level of all communes in each province, aggregating scores across three development lenses. The top 5 most vulnerable provinces are Battambang, Prevy Veng, Kampong Thom, Kandal, and Kampong Cham. In general, rural and sparsely populated areas tend to be more vulnerable. This pattern is, however, uneven. For instance, Prey Veng is the third most densely populated area but ranks sixth in terms of vulnerability. It is little exposed to floods, but people's access to high schools, hospitals, markets, and jobs is significantly poor.

Table 13: Results – Intermediate and Aggregated Scores per Province

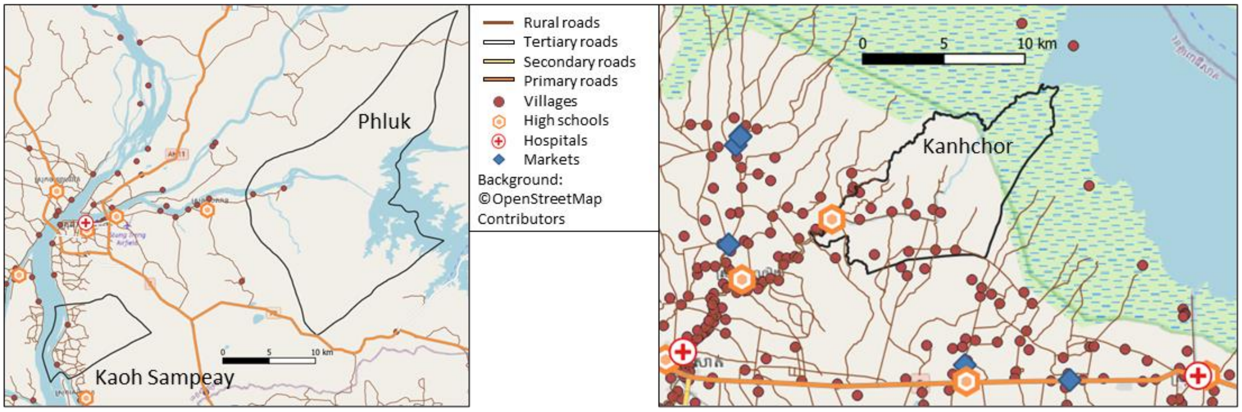
Province code	Province	Population	Road Criticality Score			Adjustable Weight (0-5)	Prioritization Score
			Inclusiveness (0-100)	Human Development (0-300)	Logistic Supply (0-200)		
01	Banteay Meanchey	861,883	1	94	41	1	45.33
02	Battambang	997,169	81	208	121	1	136.67
03	Kampong Cham	899,791	15	131	49	1	65.00
04	Kampong Chhnang	527,027	82	33	10	1	41.67
05	Kampong Speu	877,523	14	11	4	1	9.67
06	Kampong Thom	681,549	35	78	136	1	83.00
07	Kampot	593,829	15	3	2	1	6.67
08	Kandal	1,201,581	5	190	52	1	82.33
09	Koh Kong	125,902	68	10	0	1	26.00
10	Kratie	374,755	71	28	4	1	34.33
11	Mondul Kiri	92,213	31	2	0	1	11.00
12	Phnom Penh	2,281,377	1	107	5	1	37.67
13	Preah Vihear	254,827	38	5	0	1	14.33
14	Prey Veng	1,057,720	33	180	69	1	94.00
15	Pursat	419,952	72	56	26	1	51.33
16	Ratanak Kiri	217,453	33	2	1	1	12.00
17	Siemreap	1,014,234	9	40	18	1	22.33
18	Preah Sihanouk	310,072	12	13	7	1	10.67
19	Stung Treng	165,713	28	21	3	1	17.33
20	Svay Rieng	525,497	0	1	16	1	5.67
21	Takeo	900,914	41	55	14	1	36.67
22	Otdar Meanchey	276,038	11	4	4	1	6.33
23	Kep	42,665	36	0	0	1	12.00
24	Pailin	75,112	100	2	5	1	35.67
25	Tboung Khmum	776,841	32	10	3	1	15.00

Table 14 presents the 15 communes that have the highest Prioritization Score, which indicate that rural roads in these communes should be prioritized for improvement. Figure 4 shows the maps of three communes with the highest integrated scores: Phluk and Kaoh Sampeay in the north-eastern province of Stung Treng and Kanhchor in the western province of Pursat. Such maps help understand the geographic and socio-economic situation of the communes and identify the most critical roads for these communities. All three communes are located in a flood-prone areas, in rural provinces with few employment opportunities, and are marked by a high poverty rate. Phluk, the commune with the highest priority, is located below a hydroelectric dam on the Tonle Srepok river; Kaoh Sampeay is situated along the Mekong River; Kanhchor is on the banks of the Tonle Sap Lake. Phluk is only reachable via a single rural road, and the first hospital is about 30 km away using this road. Kaoh Sampeay is also very dependent on a flood-prone rural road. Kanhchor has better access to a high school but is one of the communes the most vulnerable to floods.

Table 14: Results – Top 15 Communes Where Rural Roads Should Be Prioritized for Improvement

Commune code	Commune name	Province	Road Criticality Score			Adjustable Weight (0-5)	Prioritization Score
			Inclusiveness (0-100)	Human Development (0-300)	Logistic Supply (0-200)		
020404	Prey Khpos	Battambang	49	57	100	1	34.33
010209	Ruessei Kraok	Banteay Meanchey	12	168	12	1	32.00
140807	Prey Pnov	Prey Veng	9	114	62	1	30.83
040301	Phsar Chhnang	Kampong Chhnang	50	132	2	1	30.67
010211	Soea	Banteay Meanchey	17	103	61	1	30.17
020104	Chheu Teal	Battambang	30	113	35	1	29.67
030107	Sambour	Kampong Cham	21	93	62	1	29.33
121003	Preaek Ta Sek	Phnom Penh	11	159	0	1	28.33
140810	Reab	Prey Veng	9	108	50	1	27.83
020806	Kampong Prieng	Battambang	55	76	31	1	27.00
020406	Kdol Ta Haen	Battambang	41	58	62	1	26.83
020405	Ampil Pram Daeum	Battambang	45	51	59	1	25.83
020810	Vaot Ta Moem	Battambang	25	92	34	1	25.17
121001	Chrouy Changvar	Phnom Penh	3	139	0	1	23.67
020607	Kakaoh	Battambang	35	25	81	1	23.50

Figure 4: Map of the three communes with the highest global vulnerability scores



7. Limitations of the Analysis

This analysis has some limitations linked to data available or simplification of methodology that could eventually be addressed in future works.

In general, the validity of the results is bounded by data quality. Some of the datasets did not have the adequate resolution or were relatively outdated. The values of agriculture production were taken from a global model developed by the International Food Policy Research Institute. The model estimates yearly output on a 10 km by 10 km grid. Such a yearly average did not allow us to incorporate the seasonality of crops. We used the 2010 results, the latest but slightly outdated estimates provided by this model for the region. Without direct data on logging and fishing activities, we calculated estimates based on global fishing intensity and deforestation models. Such downscaling process induces uncertainties. The latest business census was released in 2011, which is also relatively outdated compared to the 2019 population census. In the absence of inventory data specific to Cambodia, we used the data used in Colon et al. (2021) for Tanzania, the only available dataset on inventory per sector for a developing country.

Approximations had to be made to harmonize datasets on villages that were using different geocoding. The only village dataset that had geographic coordinates was the 2008 population census. The 2011 business census, the 2019 population census, and the 2021 poverty survey had all different geocodes for villages because some provinces, communes, or villages have been split over the past decade, and new villages have been created. We mapped all these data into the 2008 geographic coordinates by making ad-hoc assumptions to fix inconsistent geocodes. We also partly incorporated the changes in geocoding using World Bank's information on administrative changes.

Regarding the accessibility model, we did not model the usage of mid-range waterways besides river-crossing ferry boats due to a focus on roads and a lack of data. They could have an impact on the accessibility pattern, especially during the rainy season. Similarly, congestions were not considered in this analysis. They have a sizeable effect on travel times, especially in urban and suburban areas. This aspect was left out of the scope because the focus was on rural areas.

The employment opportunity access analysis was run at the commune level and not at the village level for computational consideration. Two assumptions were made. First, within a commune, anyone can reach all job opportunities of the commune, whatever the extent of the commune. Second, if someone can reach the main village of a commune in less than 60 minutes, they can access all the job opportunities of that commune, wherever they are actually located. These assumptions tend to overestimate the number of jobs that people can access. But they are likely to have a limited impact on the relative score between communes so that the analysis can be used for a prioritization purpose. Disaggregating this employment analysis to the village level could provide better absolute estimates. This indicator does also not take into account the demand for jobs. An isolated commune may have access to limited number of jobs, which, however, could be well enough for the local community. Additional data on local job markets, such as local unemployment rate, could be used to better gauge the employment opportunities.

Similarly, the criticality patterns generated by the supply chain model are robust and could be used for prioritization. But taken in isolation, the absolute monetary estimates present significant uncertainties due to heterogeneous data quality, the probabilistic reconstruction of supply chains, and simplifying behavioral assumptions on production and price adjustments.

The model relies on MRD's approved assumptions linking the road class with their theoretical road engineering characteristics. The actual characteristics of individual roads may differ from the assumptions. Field observations would be critical to check these assumptions and refine them. Moreover, the assumption on whether a road becomes impassable is purely based on the floodwater level. This is reasonable for lowland areas where waterlogging can occur. But in hilly or mountainous areas, passability can also be restricted by weather-induced erosion or landslides, which is not represented in the model.

A critical limitation is the resolution of flood maps. They were derived from a global digital elevation model with a resolution of 30 meters by 30 meters, which is too coarse-grained to identify the height of floodwater on specific roads. In particular, the embankments of the road are likely to be higher than the surrounding area. The passability thresholds aim to address this limitation, although they are very general and could not be adjusted to each road's characteristics. These flood maps were the best data available for this region at the time of analysis. Higher resolution elevation maps, using lidar or drone images, would be critical to improve this analysis.

Our accessibility model assumes that everyone has equal access to road vehicles. In reality, gender, poverty, and other indicators affect people's access to different modes of transport, which is likely to exacerbate gaps in travel time (Hasanbasri et al. 2021). Using such data could also allow us to interpret the results of the analysis from a social inclusion angle.

Climate change is likely to change the intensity of floods per return period. In this context, it may be necessary to reassess the results with modified flood maps based on projected climate scenarios for Cambodia at a relevant time horizon for road financing.

Model inevitably carries limitations, especially when it ingests such a large spectrum of data and is used at detailed spatial resolution. It is crucial to grasp those limitations for decision-making by exploring the input data and the results on maps at different scales. The visualization tool that is being developed for this project will meet this purpose. Beyond those presented in this section, identifying potential inconsistencies will be helpful to improve the method further. Due to data limitation, the multicriteria analysis focuses on communes rather on roads. In theory, there can be cases in which a high priority road segment falls within a low priority commune. Because communes are rather small, and contains, on average, only 32 km, such cases are very unlikely. But this consideration underlines that very small road segments can remain unnoticed if we only look at the results at the commune level. Higher resolution flood maps and road data are needed to address gap. That is why we recommend decision-makers to visually interact with the data and the results and to complement this analysis with field observations.

8. Conclusions

Cambodia is subject to floods which often disrupt road transport, leading to significant consequences for the population. Almost 30% of the population needs more than one hour to reach a hospital; the figure reaches over 43 percent when a 50-year flood hits. This vulnerability also affects economic development. In such flood events, about 55% of agricultural production cannot be transported to a market within an hour and access to jobs within an hour decreases by 28 percent. There is a need to invest in infrastructure and maintenance and adapt the road network to climate change. Where should investment be targeted? This paper provides a framework to prioritize road interventions, which uses diverse large data sets and geospatial transport simulations. These analyses deliver nine vulnerability indicators covering a large spectrum of concerns, including exposure to floods, road fragility, poverty, access to essential services, ability to reach jobs and markets, and supply chain criticality. The nine indicators were equally weighted and aggregated into one global vulnerability score to facilitate the prioritization of road investment. The choice of indicators can always be questioned and revised in relation to stakeholder's priorities. In particular, how indicators are weighted and combined is crucial and should reflect stakeholder preferences.

The results are available for the whole country, yet they are provided at detailed spatial resolutions, i.e., Cambodian communes, with an average size of about 110 km^2. Some of the indicators are also available at the level of villages. Such a fine resolution enables a precise targeting of investments. This analysis features significant innovations compared to the previous geospatial study run on a few provinces (Espinet Alegre et al., 2020). It incorporates the data of the latest population surveys (2019) and includes the poverty rate as one crucial indicator. Thanks to detailed firm-level data, the ability of Cambodians to reach workplaces could be assessed by the Employment Opportunity Access indicator. A supply chain analysis was carried out to pinpoint the most critical roads to connect Cambodian businesses using additional socio-economic data, including trade and national account data. These three indicators help capture the role of roads in creating economic opportunities, especially in poor areas.

We found that the most vulnerable communes are located in the north-eastern, central, and western provinces, such as Stung Treng, Koh Kong, and Pursat. Rural and sparsely populated areas tend to be more vulnerable, but this pattern is significantly uneven. For instance, Prey Veng is the third most densely populated area but ranks sixth in terms of vulnerability. The situation of each province and commune is specific and relates to their geography, economic activities, and equipment in basic facilities. That is why a prioritization that would only be based on raw numbers such as population or road density would miss where roads are the most needed. The method described in this paper turns the available data into context-specific indicators which capture the role of roads for people. Such an approach can guide the more effective use of financial resources and better reflect political priorities.

The study also evaluates alternative risk reduction investments, namely, strengthening of bridges, improvement of drainage and road surface. Even though these road upgrades were modeled using simple, country-wide assumptions, the analysis quantifies their national potential for enhancing resilience. It should be complemented with an assessment of the costs of these measures using road-specific data. There is, of course, ample room for improvements, which we highlighted in detail in Section 7. Acknowledging potential data gaps and simplifying assumptions, we recommend combining these findings with field knowledge to develop practical recommendations.

A major innovation of this analysis is to connect transport resilience with community well-being and economic development, which was enabled by micro-level firm data. The supply chain analysis, in particular, reveals the importance of a resilient transportation system for the economy. It captures the potential impacts of transport disruption on price, a crucial mechanism that was observed during the Covid-19 pandemics. Such ab approach can help bridge the gap between infrastructure studies and macroeconomics.

9. Recommendation for Applications

This report presented the geospatial analysis and its main insights. The method helps prioritize communes for upgrading rural roads in the context of floods. The study captures a diversity of co-benefits and local factors related to roads, which are not routinely considered in road upgrade decisions, such as access to critical services, farmers' ability to reach markets, poverty, or supply chain criticality. In the decision-making context of Cambodia, the commune priority list can be used, for instance, to tighten recommendations when deciding between a few road segments to be prioritized. In particular, Provincial Road Departments could use this prioritization framework to complement and validate their assessment.

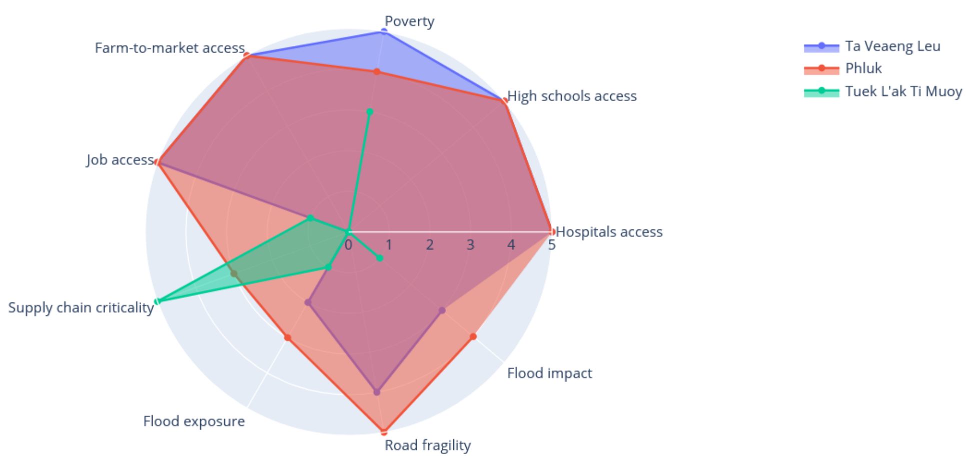
This analysis can be updated and adapted to the real-world decision-making process. To that end, we recommend that decision-makers get a grasp on the method and the results to extract the information that most fits their needs. To that end, a visualization tool is being developed and will be handed into MRD. It will feature an interface that allows users to interact with all input data layers and results using maps and graphs. They will be able to zoom in and out from the country level down to the road level and navigate across administrative scales: country, provinces, districts, communes, villages. This process is crucial to ensure that the results are properly used and to identify potential data collection efforts to address current limitations. This section provides recommendations on how this tool can be used for actual road prioritization and decision-making.

First, it is of utmost importance to visually explore the data and results in all their indicators and level of detail. Such activity, carried out by local experts and stakeholders with field knowledge, is necessary to check consistency and significantly contribute to building stakeholder confidence in the analysis. It can also help identify potential data inconsistencies and avoid misled decisions.

The diversity of indicators produced in this analysis may sometimes be hard to handle at first. Some data visualization charts are tailored to handle such complexity and greatly help make sense of the results. For instance, Figure 5 shows a so-called radar or spider chart. It is used here to compare the nine vulnerability scores of three communes: Ta Veaeng Leu in Ratanak Kiri, Phluk in Stung Treng, and Tuel L'ak Ti Muoy in Phnom Penh. The larger the colored area, the higher the aggregate vulnerability score. It allows users to grasp the relative vulnerability pattern between the three communes quickly. We observe that the two rural communes are more vulnerable than the urban commune in Phnom Penh. Phluk's scores dominate those of Ta Veaeng Leu, but the latter is slightly poorer. These two communes are well exposed to floods and have poor accessibility, unlike Tuel L'ak Ti Muoy. The latter is, however, much more critical for supply chains and has a significant level of poverty.

Using the global vulnerability score is a valuable starting point for prioritization. But it is crucial to understand that the final ranking is highly dependent on the weight put on each individual score. Here, we adopted a simple approach, in which all scores were given the same weight. This choice is not neutral and has substantial consequences. For instance, a third of the score is driven by flood-related indicators: flood exposure, road fragility to floods, and flood impact. This may be too much or not enough, depending on the priority. Similarly, access to hospitals is given the same importance as access to jobs. This may be discussed and revised according to stakeholders' priorities. In the tool, users will be allowed to adjust the weights. Playing with those numbers helps understand how the vulnerability ranking reacts to those changes. When it comes to setting the priority, the choice of the weights should be carefully made and agreed upon with the relevant stakeholders.

Figure 5: Illustrative Commune-Level Vulnerability Ratings.



Additional information is needed to move from the selection of high-priority areas to picking the roads to improve. Visualizing the maps of those areas and their associate vulnerability scores allows experts to identify road-related challenges quickly. Accurate data on road conditions and field observations are crucial to formulating practical recommendations.

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