Network Analysis

ADVANCED SIMULATION

EPA133a

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Introduction

In the Advanced Simulation course, our team has developed a computational model that represents Bangladesh's road and bridge network. During previous assignments, we refined the raw data on transportation infrastructure, designed a simulation model, and created a representative network model. In this assignment, we critically analyze these datasets to identify the most promising investment options for the World Bank, the project's financial stakeholder.

The World Bank's motivation to improve the transportation network of Bangladesh is twofold. Firstly, Bangladesh is a developing country where around 20.000 traffic fatalities are estimated yearly due to poor road quality, design and the adverse roadway and roadside environment (Hoque et al., 2011). Secondly, Bangladesh is a low-lying costal country, where around 80% of the land is engulfed in the Bangladesh Plain (Wikipedia contributors, 2024), an alluvial and fertile area where most elevation levels are below 12 meters (Topographic Map, 2024). The geographical characteristics of Bangladesh thus expose it to major natural events such as flooding (Rahman and Rahman, 2015) which lead to the displacement of millions of residents (Akter, 2010) and increase economical instability (Botzen et al., 2019).

In the following analysis we will determine the top 10 most valuable investments in terms of roads and bridges, in relation to the geographical characteristics of Bangladesh. These investments will be ranked from most impactful to least impactful considering their vulnerability in the face of natural disasters and criticality within Bangladesh's transportation network. These results will be employed by the World Bank to strategically improve the resilience and safety of the determined road components, hopefully lowering the impact of environmental events on the country's economy.

The scope of our research is limited to the macro-level natural disaster predisposition of Bangladesh, incorporating the entire set of road components available in data. Our analysis does not attempt to solve the fatality rate resulted from other factors such as the poor design of junctions (Hoque et al., 2011) mostly due to limited time and data on the topic.

1 Methodology

The ranking of the top 10 roads and bridges for criticality and vulnerability that promise the best return of investment fo the World Bank is obtained by attributing and ordering the scores of all components in the Bangladesh transportation network. The score of each road component is normalized and lays between 0 and 1. In the following subsections, we will dive into the definitions and mathematical formulation of these two characteristics of infrastructure parts.

The pre-processing of data and the calculation of the metrics can be further seen in the *model* sub-folder of the *data* directory present in this submission folder.

1.1 Criticality

Criticality is a characterization of a road component that captures its importance relative to the entire network. Relative importance can be defined based on an object's consequences during failure(Jenelius et al., 2006) or it can remain neutral to risk probabilities (de Oliveira et al., 2016), resulting in a multitude of different formalizations for criticality. For the purpose of our study, the relative importance of a component will be assessed under Bussines-As-Usual (BAU) scenarios, where no natural hazards intervene, and can be asserted based on socio-economical and geopolitical criteria.

To find the ideal metric to quantify criticality in Bangladesh's road network and calculate each component's criticality score we follow the guidelines described in Jafino et al., 2020, Figure 5. This article determines the steps needed to select the most appropriate metric to evaluate criticality:

1. Select the functionality to be observed
2. Select the ethical paradigm of your study
3. Select aggregation level
4. Filter among similar metrics

5. Select between final metrics

The study by Jafino et al., 2020 compares 17 different metrics among each other to finally describe the above framework. The tests and comparisons in this article are relative to the road network of Bangladesh, and will be used without further validation in our project on the same network.

Our project aims to report the ideal investment opportunities for the World Bank that will help stabilize the socio-economical status of Bangladesh. This directs our team's focus toward the road elements that are important in keeping the transport services constant and reliable. We opt for **connectivity** as the functionality dimension we want to focus on, which evaluates and assigns the highest criticality to the objects without which locations of interest are disconnected.

Since there is a limited pool of funds for investments, our group suggests to maximize the collective benefit for Bangladeshi society. With the opportunity to intervene only on 10 roads and bridges, our group decided to give precedence to heavy traffic areas in our analysis and elect the **utilitarian** ethical dimension.

To deliver a comprehensive set of conclusions, our project takes the entire geographical region of Bangladesh into consideration, leading us to select **network-wide aggregation** for the aggregation dimension.

With all three attributes of our study being identified, we find there is only one metric that fits all of our requirements: Unsatisfied demand (Baroud et al., 2014, Qiang and Nagurney, 2012). The formula for this metric originally takes disruptive events into consideration:

$$CI_{zu,i}(t_r|e_j) = \frac{u(x(t_0)) - u\left(x(t_0); x_i(t_d|V_i^j)\right)}{\max_i \left\{u(x(t_0)) - u\left(x(t_0); x_i(t_d|V_i^j)\right)\right\}} \cdot T_u(x(t_0)|V_i^j) \tag{1}$$

However, since later on we explain that the effect of disruptive events is considered under vulnerability alter on, we eliminate this parameter from the original formulation. We also decouple criticality from vulnerability, and eliminate the weights from the formula, to measure pure criticality and avoid overlap with the second attribute. The final version of the criticality metric used in our assignment to score each road component in the Bangladesh road network is:

$$CI_i = \frac{u(x(t_0)) - u(x(t_0); x_i)}{\max_i \{u(x(t_0)) - u(x(t_0); x_i)\}} \cdot T_i \tag{2}$$

This metric quantifies the relative drop in system performance caused by the failure of a component, normalized across all components, and weighted by how long the network takes to recover from the disruption. It helps identify which roads or bridges are inherently most critical to the transport system's functionality, independent of their vulnerability. The final general criticality index formula (2) consists of the following terms:

- CI_i: The criticality score of road or bridge component i, reflecting its overall importance to the functioning of the network.
- $u(x(t_0))$: The network's total performance under normal, undisturbed conditions.
- $u(x(t_0); x_i)$: The network performance after component i has been removed or disabled from the system.
- $\max_i \{u(x(t_0)) - u(x(t_0); x_i)\}$: A normalization term that scales criticality scores between 0 and 1 by comparing each component's impact to that of the most disruptive one.
- T_i: The estimated time required to restore full network functionality after the failure of component i (e.g., through reconstruction, rerouting, or repair).

We expect a unique ranking to result from this definition of criticality, as Figure 3 of Jafino et al., 2020 indicates this quantification is highly inconsistent with other metrics, making it insightful.

The AADT data (Annual Average Daily Traffic), disaggregated by vehicle type, can be used to approximate road usage or network throughput, which is the core of the $u(x)$ function used in the formula. In particular:

- $u(x(t_0))$: Average AADT over the full network. This value represents the system's overall performance under normal, undisturbed conditions.
- $u(x(t_0); x_i)$: Average AADT over the full network, excluding the component i, assuming no detour is possible (i.e., that the load on x_i is entirely lost). Due to the lack of AADT data for bridges, the AADT of the road it is part of is used.

These values allow for the computation of the relative performance drop caused by the failure of component i, which is essential for calculating its normalized criticality score. However, it is important to note that this formulation does not account for rerouting.

The estimation of time to recovery (T_i) for rural roads and bridges in Bangladesh requires a context-sensitive approach that accounts for both the physical attributes of infrastructure and institutional constraints. Drawing from the Post-Disaster Needs Assessment (PDNA) and the Local Government Engineering Department (LGED) sectoral reports, recovery timelines are significantly influenced by geographical location, particularly proximity to coastal, haor, and char areas, which are more prone to extreme weather events and delayed access during recovery (Government of Bangladesh, 2022; LGED, 2023). Moreover, historical recovery performance from previous projects—such as those documented in the Asian Development Bank ADB validation report—reveals that even planned maintenance projects can face execution delays of 2–3 years due to procurement inefficiencies, environmental clearances, and land acquisition issues (Asian Development Bank, 2010).

In addition, road length and type play critical roles; larger-scale or elevated rural roads require longer periods to reconstruct, especially where embankments or drainage structures are needed. The availability of maintenance funding further constrains timelines. While LGED oversees 82% of the rural road network, it receives only one-fourth of the necessary annual maintenance budget, creating a persistent backlog that slows recovery across all asset types. Finally, local government involvement (LGI) remains limited in terms of financial contributions, even though LGIs may be operationally responsible for sections of the rural road network (LGED, 2023).

The PDNA indicates that full rural road reconstruction may span 6 to 12 months depending on damage severity and geographic constraints. The ADB's validation report shows that large-scale road contracts required several years to complete due to procurement delays and capacity bottlenecks. Considering typical rural road segments between 1–3 kilometers in length, and adjusting for construction delays observed by LGED and underfunding of maintenance backlogs, a practical planning estimate ranges from **60 to 180 days per kilometer** for full restoration.

Therefore, T_i can be modeled as a function of asset type, condition, geographic location, and length, with realistic durations ranging from 6 months to 4 years, depending on these interacting variables. Institutional factors are not included, since the scope of the analysis is to prioritize infrastructural investments.

$$T_i = T \cdot \frac{L_i}{L_{\text{avg}}} \cdot C_i$$

- T is the average repair time of the road per kilometer.
- L_i is the length of the component, and L_{avg} is the average segment length across the road.
- C_i represents a coastal exposure factor, reflecting increased recovery difficulty in regions affected by flooding, cyclones, or erosion (World Bank, 2022).

Due to lack of time and resources the variable C_i will not be implemented, but it could easily be done by comparing the position of the road segment or the bridge (lat/lon data) with geographic data on climatic hazard or by calculating the distance from the coastline.

Moreover, T is constant and the metric should be expressed in a range of $[0, 1]$. Therefore, the tie constant can be neglected, and the average length can be switched with the maximum value to ensure normalization. The following metric will be implemented:

$$T_i = \frac{L_i}{L_{\text{max}}}$$

1.2 Vulnerability

Vulnerability is the road network's capability to operate under different disruption scenarios (Lu et al., 2021). The disruptive events considered in our project are environmental due to Bangladesh's at-risk geographic traits. Based on the availability of data online and the geographical environment of the country, the following natural hazards are considered:

- River flooding
- Earthquakes
- River bank erosion

To obtain a list of the 10 most vulnerable roads and bridges in Bangladesh, the components are rewarded with a vulnerability score. The final vulnerability metric results from normalization, such that it can be a value between 0 and 1, and comparable to criticality.

The vulnerability score of a component will be assigned based on how likely it is to sustain damage across natural events. The consequences of a component's closure are tackled by the criticality metric and avoided in vulnerability. This approach tackles the serviceability aspect of the vulnerability definition as proposed by Berdica, 2002. We calculate vulnerability based on Husdal, 2010 and the general structure of our metric can be seen in Formula 3.

$$V = \sum C_i I_i \tag{3}$$

Where:

- V is the overall vulnerability score of the component.
- C_i is the weight assigned to vulnerability category i, representing its relative importance. (Constant)
- I_i is the impact score for the component in category i, reflecting how severely it is affected.

This approach allows the aggregation of multiple vulnerability dimensions into a single score. For the purpose of our study, the considered categories and their respective weights are:

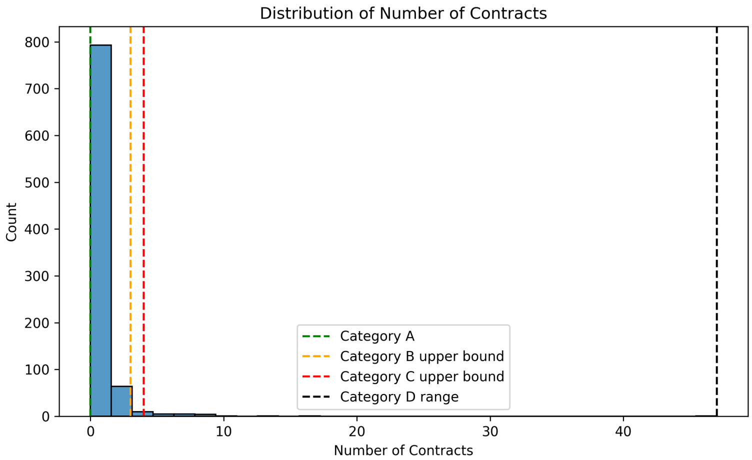
- Flood risk / weighted by flooding likeliness in the area
- Earthquake risk / weighted by earthquake risk in the area
- River bank erosion risk / weighted by river bank erosion likeliness in the area

The impact scores for bridges are assigned from 1 to 4, representing the condition the bridges are in, 1 being best and 4 being worst state. The numbers are assigned by translating A-B-C-D categories. The impact score for the roads is estimated based on the amount of work being done on a road, and categorized from A to D as well. The categorization is based on the distribution of road works and can be adapted to another assignment by changing the code in the `model` subfolder. Figure 1 illustrates the correlation between a road's assigned category as determined by both the length of the repair and the number of contracts. To compute the vulnerability metric, the road categories are translated to numerical values similar to the bridges.

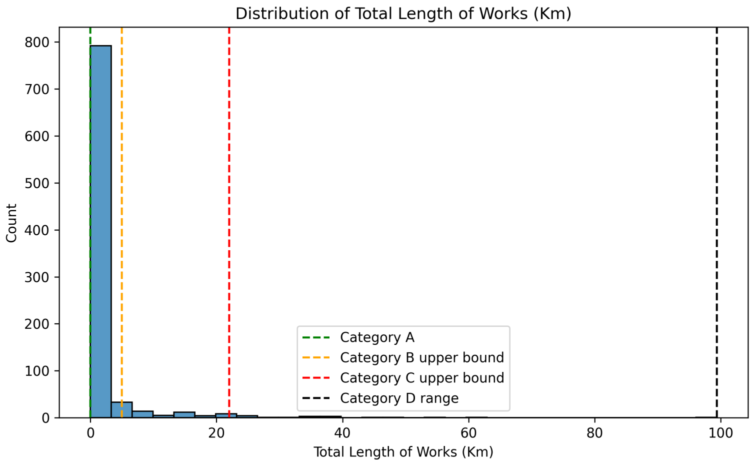
1.2.1 Extracting and analyzing the data

The dataset *Bangladesh - Hazards (Drought risk, Earthquake risk, Flood risk, and River erosion risk)* was used to obtain the data needed for the vulnerability scores. The dataset provides spatial data on various natural hazards in Bangladesh. It includes separate datasets for drought risk, earthquake risk, flood risk, and river erosion risk, each with distinct attributes. The data originates from the Bangladesh Agricultural Research Council (BARC) and has been updated by organizations such as the World Food Programme (WFP), Map Action, and the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) Office, 2013.
The datasets relevant to our vulnerability scores were `bgd_nhr_earthquake_barc`, `bgd_nhr_floods_barc`, and `bgd_nhr_rivererosion_barc`.

The risk scores for the flood risks in the `bgd_nhr_floods_barc` were as follows:



(a) Distribution of Number of Work Contracts for the Roads.



(b) Distribution of Total Length of Works on Each Road.

Figure 1: Side-by-side comparison of the distribution of the number of contracts (left) and the total length of works (right), each indicating category cutoffs for A, B, C, and D.

- 0: *Not Flood Prone*
- 1: *Severe River Flooding*
- 2: *Moderate River Flooding*
- 3: *Low River Flooding*
- 4: *Severe Flash Flooding*
- 5: *Moderate Flash Flooding*
- 6: *Low Flash Flooding*
- 7: *Severe Tidal Surge*
- 8: *Moderate Tidal Surge*

Because the scores were not ordered progressively but categorically, the decision was made to focus on river flooding and adjust the scores to a grading scale. This was done by only looking at the scores 0, 1, 2, and 3, and then by switching the 1 and 3 scores to create a progressive scale, where 0 is the lowest (no flooding) and 3 is the highest score (Severe River Flooding).

To assess seismic exposure of the transportation infrastructure, earthquake vulnerability zones were used from the data set. These zones are categorized using the EARTHQUF_I's attribute, which assigns each area a discrete earthquake vulnerability score. The values in this attribute represent levels of vulnerability rather than absolute magnitudes and were treated as ordinal for analytical purposes.

Although the original values were integers (0, 1, 2, 3), they conceptually correspond to progressively increasing levels of earthquake risk. Using spatial join techniques, each road and bridge point was assigned its respective vulnerability score based on the zone it falls into. The final score for each road was calculated as the average of all the vulnerability values assigned along the path of that road.

This results in a continuous scale score between 0 and 1 for each road segment. For example, a score of 0.5 implies that a road consistently falls into a zone of moderate vulnerability, while a score closer to 1.0 indicates a consistent presence in high-risk areas. This normalized approach allows for a meaningful comparison across the national road network.

To evaluate exposure to riverbank erosion, the data set was used again, where the attribute AFFECTED identifies whether a polygon is classified as vulnerable to riverbank erosion.
As this field is binary (either "Riverbank Erosion" or blank), a numerical transformation was necessary for analytical use. A binary scoring system was implemented:

- 1: *was assigned to points within "Riverbank Erosion" zones.*
- 0: *Elsewhere*

This transformation enabled the calculation of the average erosion score per road, interpreted as the fraction of the road that intersects erosion-prone areas.

For example, a road with a score of 0.75 has 75% of its segments affected by river erosion. This method allowed for consistent quantification of risk and enabled direct comparisons across roads and bridges.

Using Python, the shapefiles of these datasets were read into a geodataframe. The shapefiles were merged based on the longitude and latitude coordinates with the roads3 dataset using a spatial join. For the flood risk vulnerability, the relevant scores for the river flood risk were filtered and adjusted to be on a progressive scale, after which the average per road was calculated and normalized. For the earthquake and river erosion risk, the average score per road was calculated and normalized. The normalization was done by dividing all scores by the highest one, ensuring final values between 0 and 1.
The resulting dataframes were merged, after which the vulnerability score was calculated.

1.3 Datasets

In the assignment directory, in the folder titled *data*, the different data sources for our analysis can be found and are explained in detail in the relevant README.md files. We summarize them here as well:

- roads3, provided by the educational team
- BMMS files with bridge information provided by the educational team
- RMMS files with AADT numbers for roads, provided by the educational team
- The natural hazard datasets from the Bangladesh - Hazards dataset, obtained from the humanitarian data exchange website of the United Nations Office for the Coordination of Humanitarian Affairs.

2 Results

2.1 Top 10 Road Investments

2.1.1 Vulnerability

2.1.2 Criticality

2.2 Top 10 Bridge Investments

Table 1: Top 10 Vulnerable Roads - Bangladesh

Road Name	Vulnerability
Z7102	1.0
Z8011	1.0
R710	0.972263
N805	0.920779
N7	0.920467
N806	0.899237
R601	0.862144
R771	0.796226
Z1430	0.745946
Z1405	0.737008

Table 2: Top10 Critical Roads - Bangladesh

Road Name	Criticality
N5	0.994555
N1	0.871845
N2	0.540940
N7	0.471915
N6	0.439640
N8	0.388122
N4	0.274869
R140	0.262245
R370	0.247706
R545	0.228894

2.2.1 Vulnerability

Table 3: Top 10 Vulnerable Bridges - Bangladesh

Road	Bridge LRP	Vulnerability
N8	LRP098c	1.000000
N7	LRP193b	0.533333
Z7021	LRP029e	0.533333
R314	LRP029f	0.500000
R545	LRP111c	0.500000
Z1445	LRP016f	0.500000
R203	LRP042e	0.466667
Z1401	LRP018f	0.466667
R203	LRP054d	0.466667
R870	LRP043e	0.400000

2.2.2 Criticality

Table 4: Top 10 Critical Bridges - Bangladesh

Road	Bridge LRP	Bridge length (km)	Criticality
N704	LRP072a	1786.0	0.993692
N1	LRP037a	1408.8	0.782599
N1	LRP037a	1408.8	0.782599
N2	LRP072c	1194.5	0.664229
R820	LRP001a	1018.0	0.568247
R820	LRP001a	1016.1	0.567187
N1	LRP241a	954.5	0.530232
N2	LRP072c	924.0	0.513811
N1	LRP024a	924.85	0.513761
R870	LRP020c	917.7	0.512616

3 Discussion

3.1 Criticality Insights

3.1.1 Roads

The criticality results are dominated by **national highways** (N-roads), which is consistent with expectations. These roads are designed to handle the bulk of inter-district and long-distance transport. Notably, `N5`, `N1`, and `N2` rank as the top three most critical roads, reflecting their integral roles in connecting major urban centers and economic hubs across the country. These highways are likely corridors with high AADT (Annual Average Daily Traffic) and limited redundancy—meaning their failure would significantly degrade overall network performance.

The presence of regional roads such as `R140`, `R370`, and `R545` in the top 10 list indicates that some regional corridors also support substantial traffic or provide key redundancy to the national system. These R-roads may serve as important links in less urbanized or peripheral regions, where alternatives are sparse.

3.1.2 Bridges

Table 4 shows the top 10 most critical bridges in Bangladesh as found with our analysis. A first look at the table shows some bridges such as LRP037a and LRP001a show up twice. This is due to left side and right side roads having a different AADT value, which is then reflected in the criticiality for bridges. Using exact traffic data on bridges would have most likely changed this result, although no such data was found within the limited time-frame. Due to how criticality is measured for bridges, the length of a bridge is the biggest indicator of criticality, as the 10 most critical bridges are also the longest. Bridge length is intuitively an important factor when considering what bridges are most important, as longer bridges are more difficult to simply drive around in the case of a breakdown. It can also be noted most bridges (seven) in the top ten are on national highways, such as N1 and N2. This can be explained by the higher traffic on both roads, and correlates well with the road criticalities found earlier.

3.2 Vulnerability Insights

3.2.1 Roads

Conversely, the top roads identified for **vulnerability** encompass a broader spread of road types. While `R771` tops the list with a perfect vulnerability score, `Z7102`, `Z8011`, and `Z1430`—all district roads—also appear prominently. This reflects the exposure of these smaller, more localized roads to environmental hazards, likely due to their geographic proximity to floodplains or erosion-prone rivers. District roads are particularly susceptible due to lower construction standards and reduced maintenance funding, as noted during the estimation of recovery times in the methodology.

Interestingly, two **national highways**, `N806` and `N805`, also appear in the vulnerability list, suggesting that even high-profile infrastructure is not immune to natural risks—especially in coastal or seismically active regions. This raises concerns about the resiliency of key transport arteries and underscores the importance of integrating hazard mitigation into design and maintenance plans.

3.2.2 Bridges

Unlike roads, the most vulnerable bridges have a big spread across both national and local networks. The bridge at LRP098c on the N8 tops the list with a perfect vulnerability score, showing that even national routes are not exempt from structural risk.
Several regional and district bridges also appear prominently, including Z7021 (LRP029e), R314 (LRP029f), and Z1445 (LRP016f), all scoring 0.5 or higher. The repeated appearance of R203, with two distinct vulnerable segments, stands out and may warrant closer inspection.
This distribution indicates that bridge vulnerability is not concentrated in any one class of infrastructure, reinforcing the need for network-wide assessments and prioritization in mitigation planning.

3.3 Strategic Investment Implications

3.3.1 Roads

The contrast between the two metrics reveals an important tension for infrastructure planning: *some roads are critical but not vulnerable, and vice versa*. For instance, `N5` ranks as the most critical but does not appear in the vulnerability list, suggesting it is structurally sound or geographically resilient. On the other hand, `R771`, the most vulnerable road, does not appear in the criticality ranking, implying that while its failure would not significantly disrupt national connectivity, it poses serious local serviceability risks.

The ideal investment targets lie at the **intersection of high criticality and high vulnerability**, such as `N7`, which is present in both rankings. This road should be prioritized for reinforcement or climate-resilient upgrading, as its failure would carry both systemic and environmental costs.

By understanding both the importance and fragility of each road, decision-makers can tailor investments not just to enhance capacity, but also to fortify infrastructure against future climate and geological shocks. This dual approach aligns with the World Bank's goals of fostering resilience while enhancing network performance in Bangladesh's uniquely exposed terrain.

3.3.2 Bridges

Longer bridges were consistently the most critical, and bridges on critical roads were more critical than those on side-roads. This thus suggests Bangladesh should prioritise long bridges, and bridges on its most critical roads,

4 Limitations

4.1 Criticality

4.1.1 Roads

While the criticality metric effectively highlights essential roads within the national network, it is subject to several limitations. First, it assumes that traffic on a failed segment is entirely lost, disregarding possible rerouting or network reconfiguration, which can lead to an overestimation of a segment's importance. The metric also uses a static representation of traffic demand based on AADT, which may not reflect temporal or situational variations in road usage. Recovery time is estimated solely as a function of road length, omitting geographic, institutional, and environmental factors that significantly affect reconstruction efforts in Bangladesh.

Furthermore, by decoupling criticality from vulnerability, the metric may overlook road segments that are both highly important and highly exposed—components that should be prioritized for investment. Despite these simplifications, the metric remains a valuable tool for preliminary infrastructure assessment, especially when detailed data or simulation capabilities are limited.

4.1.2 Bridges

The criticality metric, originally designed for roads, does not apply perfectly to bridges. For exemple, it was designed with AADT in mind, which we only had for roads. Further work could include refining or expanding this metric for bridges, as well as finding more accurate and complete data on bridges. For exemple, finding traffic data, the type of traffic (heavy duty versus light duty vehicles), and which two points it connects could significantly change which bridges to prioritise. The top ten also contained repeats due to how the data was processed. Further analysis could want to merge left/right bridges as one and re-assess criticality for a new, different set of bridges.

4.2 Vulnerability

4.2.1 Roads and Bridges

The vulnerability metric provides a useful approximation of how exposed road segments are to natural hazards, but several limitations should be noted. Firstly, the metric relies on spatial overlays with hazard datasets that vary in resolution and timeliness; inaccuracies in these layers may result in misclassification of risk levels. The hazard scores—particularly for flooding and erosion—are treated uniformly across entire road segments, ignoring variations in exposure along their length. Additionally, the weights assigned to each hazard type are fixed and not calibrated based on empirical impact data, which may bias the composite score.

The approach also omits the structural condition and material resilience of roads, focusing solely on geographic exposure rather than their actual susceptibility to damage. Lastly, institutional factors such as maintenance quality or local adaptation measures are not included, which limits the ability of the metric to reflect true service disruption risks. While the metric offers a scalable way to assess environmental exposure, its simplifications mean results should be interpreted as indicative rather than definitive.

5 Acknowledgments

5.1 Task Division

During this assignment, the tasks were equally and strategically divided within the team's member as following.

- Data cleaning: Tangui and Ada
- Criticality analysis: Alessandro and Tangui
- Vulnerability analysis: Ralph and Lorenzo
- Methodology for calculating metrics: Ada

5.2 AI Acknowledgment

ChatGPT, GitHub Copilot and DeepSeek were used to assist in the programming part of this assignment. More specifically to convert flow code into working code, as well as for debugging. LLM also helped transform the researched metrics into functions to implement in the final code.

ChatGPT was also used to help with formatting in the writing of this report.

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