Using Multi-hazard and criticality analytics to strengthen road network resilience

Dr Elco Koks – Vrije Universiteit Amsterdam

Prof Travis Waller – Technische Universität Dresden

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Solving Complex Challenges Together

Rationale behind study

- Transport infrastructure is highly vulnerable to climate hazards, causing direct damage, service disruption, and broader economic and social losses
- Climate adaptation finance requires evidence-based targeting to ensure investments are prioritized where they matter most
- Our presented analysis supports the case for Type 2A and 2B climate resilience projects, which aim to explicitly reduce long-term vulnerability and steer development towards a climate resilient society
- National-scale criticality and risk analyses identify hotspots, **providing a first scoping study** to guide deeper local surveys, field investigations, and detailed engineering assessments

Part 1 – A workflow for multi-hazard resilience of national road networks

Dr Elco Koks – Vrije Universiteit Amsterdam

In close collaboration with Sadhana Nirandjan, Shadi Shirazian, Valentin Weiwad and Surender Raj

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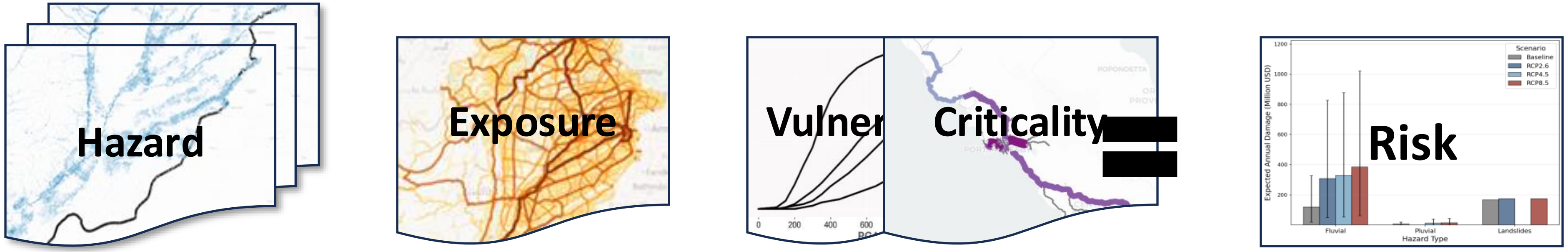
From H * E * V to H * E * V * C



- Developing climate resilience systems calls for a system-level approach
- Including criticality into our assessment allows for understanding the importance of the functioning of an asset (or a set of assets) for the entire road system
- This trickles all the way into adaptation -> an adaptation investment may not only benefit the life[time] of an asset, but also the resilience of a nearby community or the country’s trade network

Translated into a multi-tiered framework

Multiple Hazard Database

Hazard footprint

Asset-Level Exposure & Vulnerability

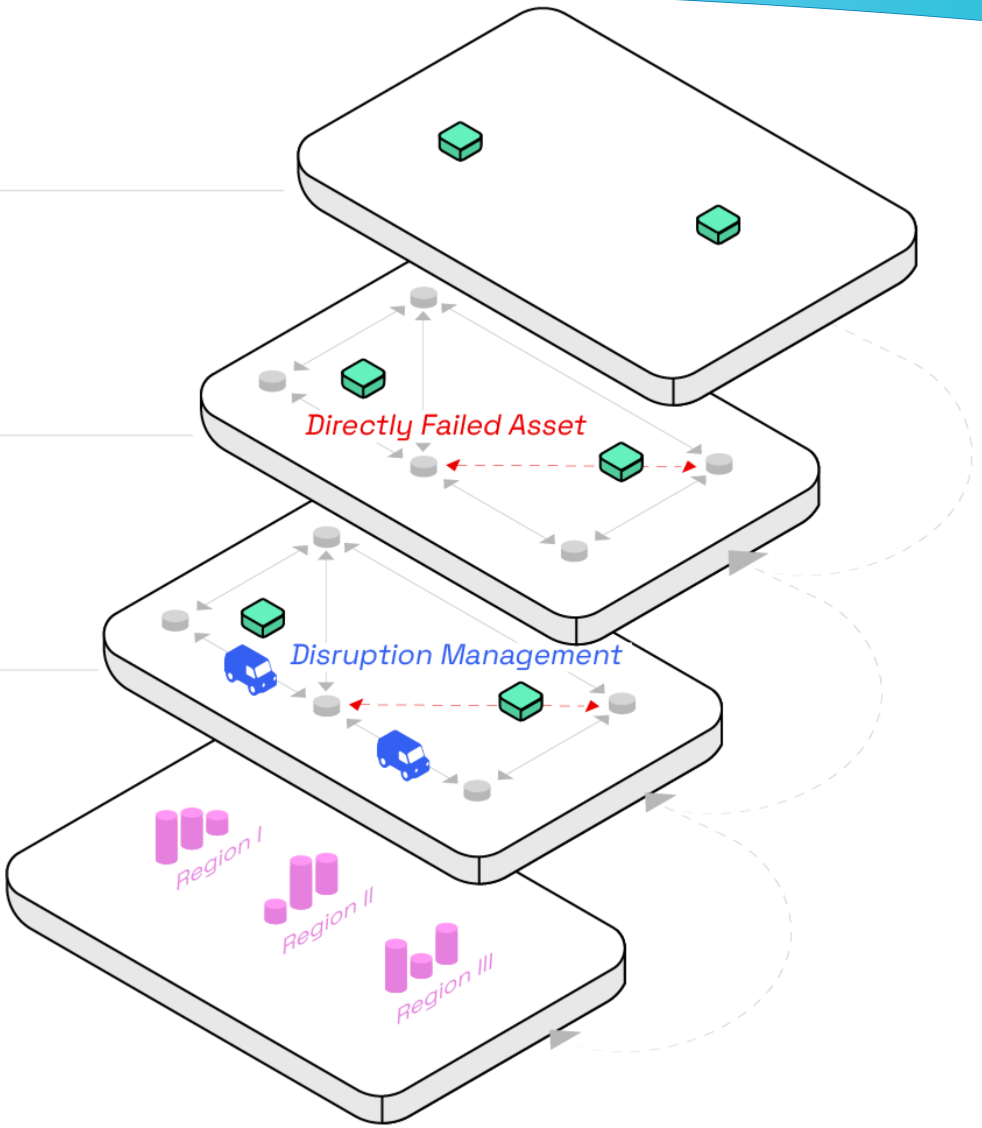
Origin/Destination

Network Criticality Analysis

Infrastructure Services

Climate Risk

Regional loss metrics



Direct physical climate risks

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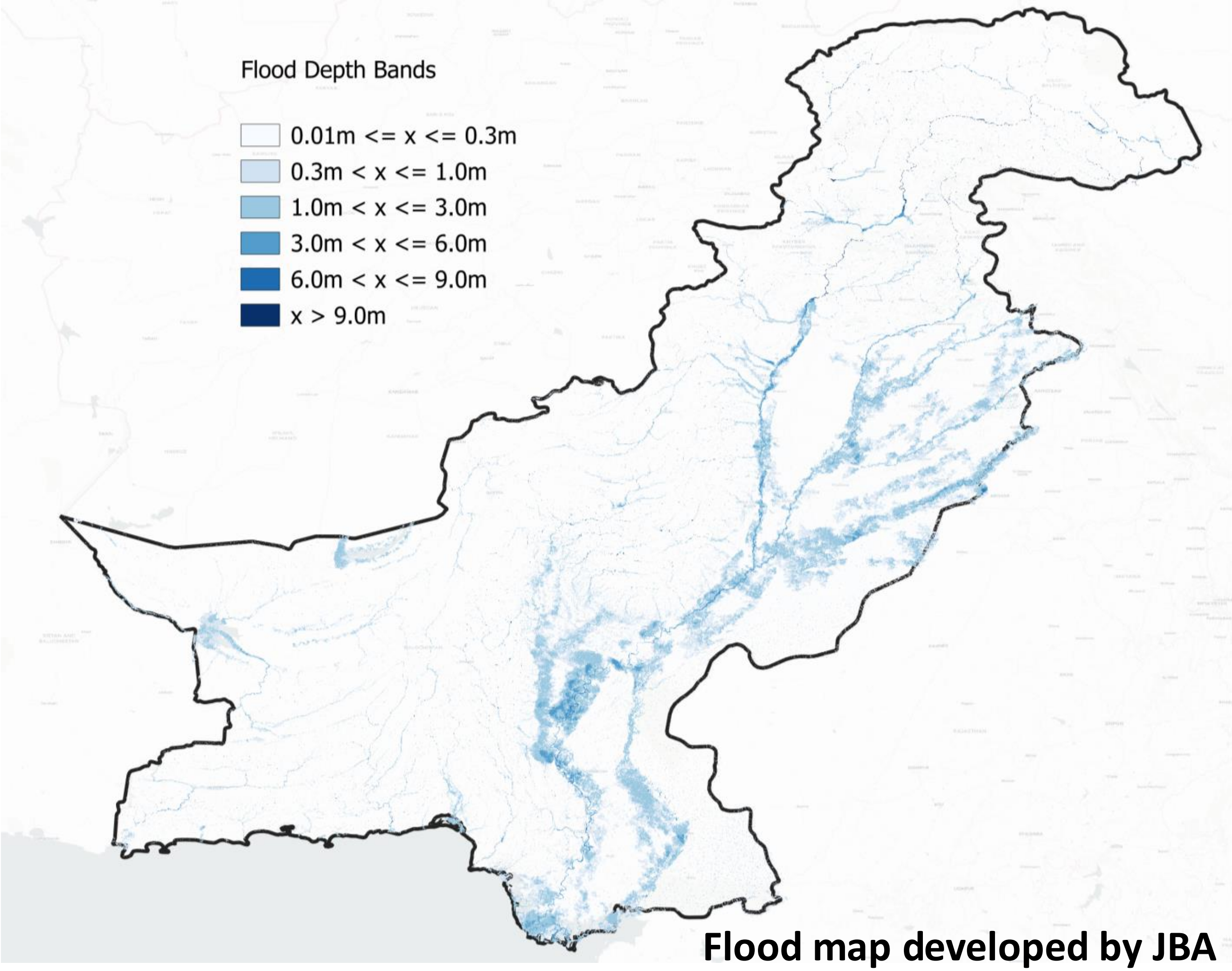
Overview of hazard data

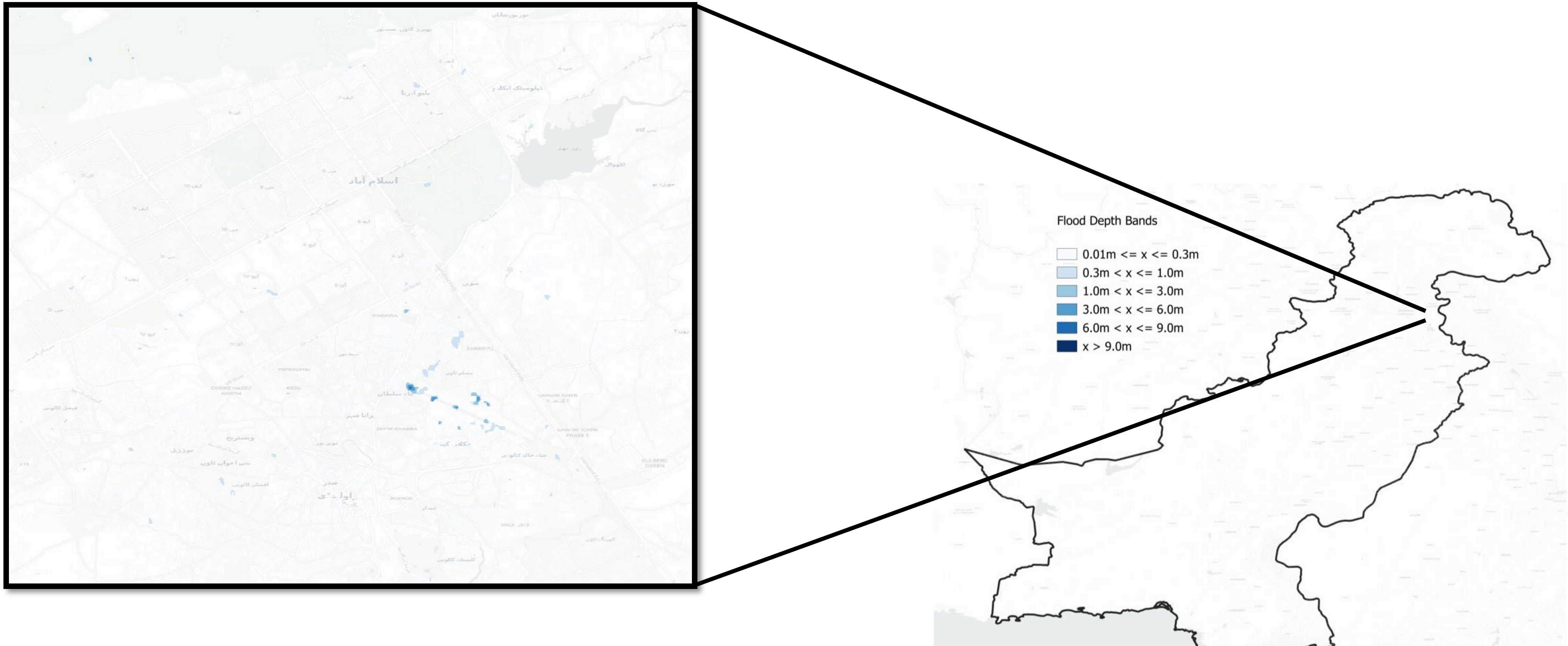
- **River & pluvial flooding**
  - Developed by JBA
  - Return periods: 1/20, 1/50, 1/100, 1/200, 1/500, 1/1500
- **Landslide susceptibility**
  - Developed through CDRI for the GIRI
  - Both earthquake and rainfall-triggered
  - Two 2100 scenarios available for rainfall-triggered landslides (low and high emission scenarios)
- **Earthquakes**
  - Developed through CDRI for the GIRI
  - Return periods: 1/250,1/475,1/975,1/1500,1/2475

Overview of hazard data: river flooding



Flood map developed by JBA

Overview of hazard data: pluvial flooding



Flood map developed by JBA

Overview of hazard data: earthquakes

CDRI Coalition for Disaster Resilient Infrastructure

Home | MAP viewer | RISK Metrics | Documentation | Contact Us

Featured (16) | Explore (5) | Pinned (0)

Peak Ground Acceleration PGA - 975 Years

Peak Ground Acceleration PGA - 2475 Years

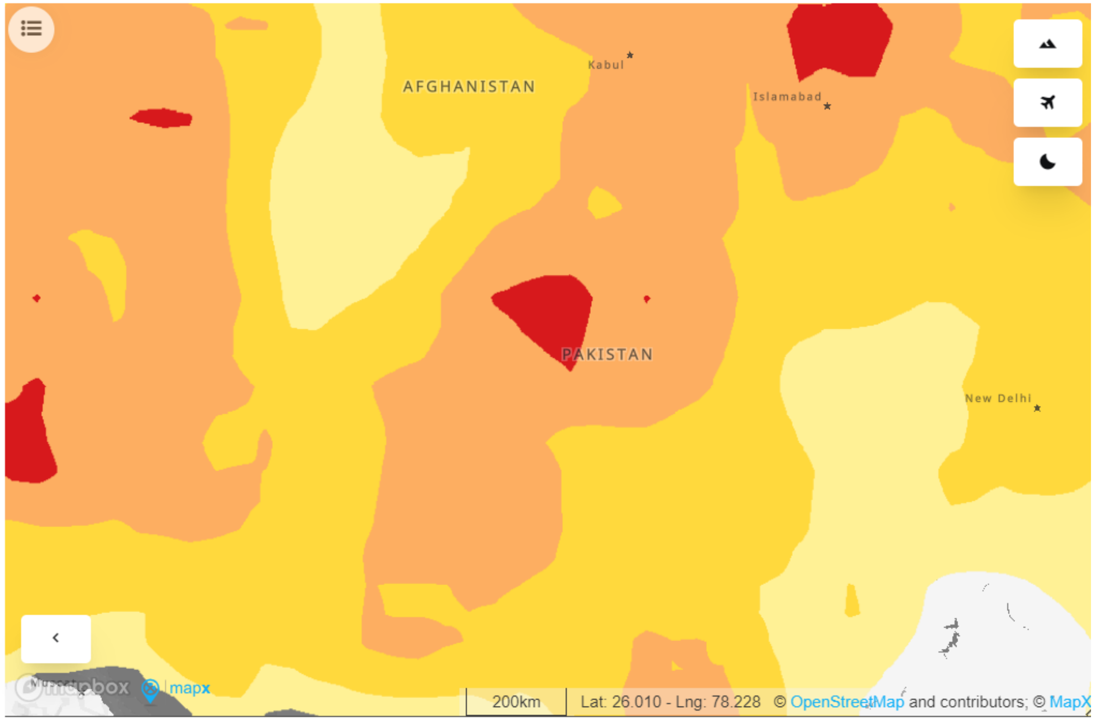
The seismic hazard map (PGA = 2475 years) indicates the mean value of peak ground acceleration (PGA) for a return period of 2475 years. The map has global coverage and a Read more

Keywords
hazard, seismic, earthquake, pga, current climate

Opacity

Share | Download dataset

Peak Ground Acceleration PGA - 1500 Years



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Overview of hazard data: landslides

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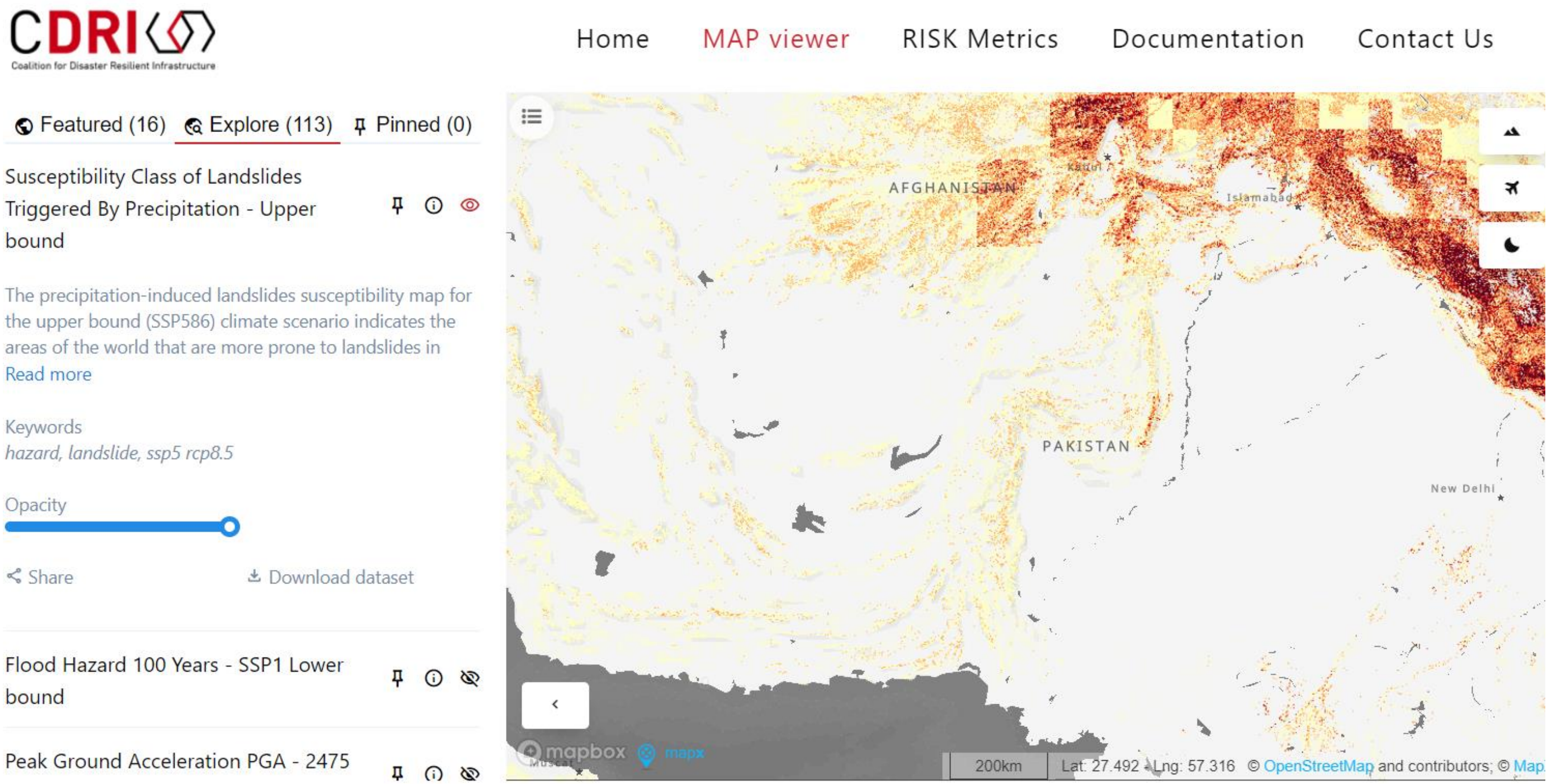

Climate change impact on flooding

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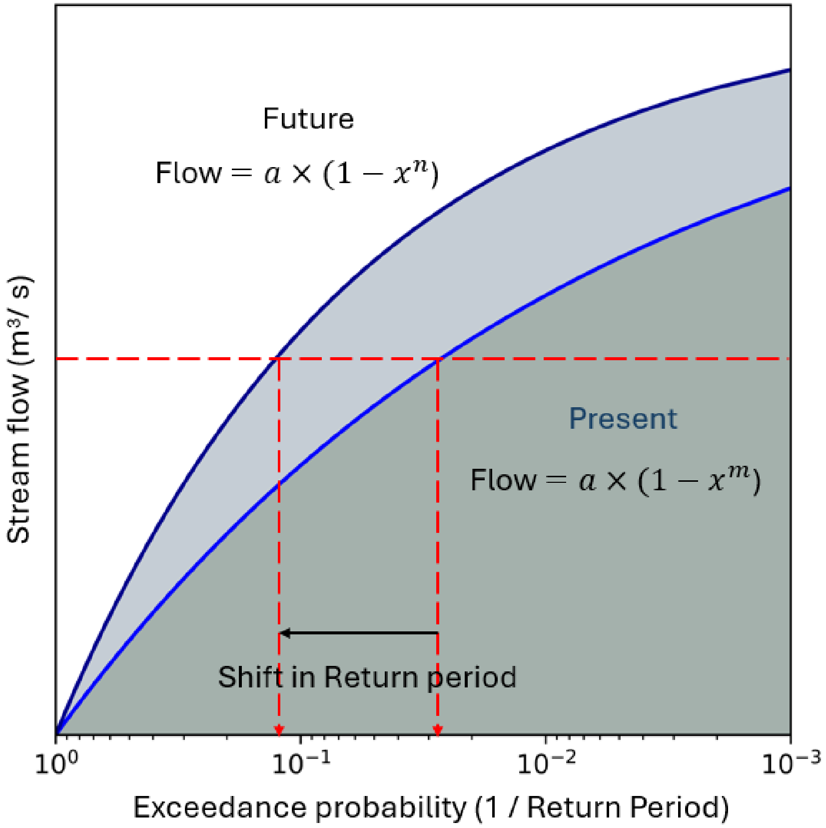
- Flood frequency is projected to change under future climate, which will shift the exceedance probability curve
- This directly affects Expected Annual Damage (EAD), as the area under the exceedance probability-loss curve will change
- Where future flood hazard maps are not directly available, we infer the shift in return periods from climate projections and adjust the exceedance probability curve accordingly
- River flood probabilities are changed based on changes in future maximum discharge flows, whereas pluvial flood probabilities are changed based on changes in future rainfall probabilities



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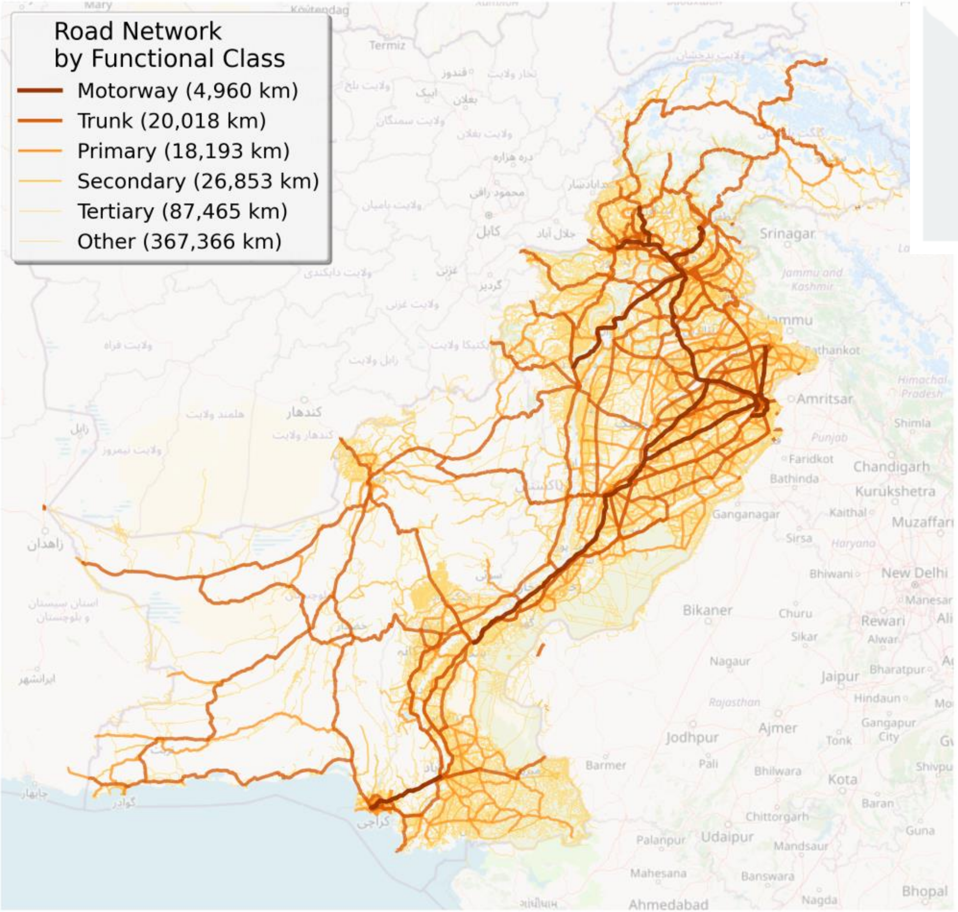
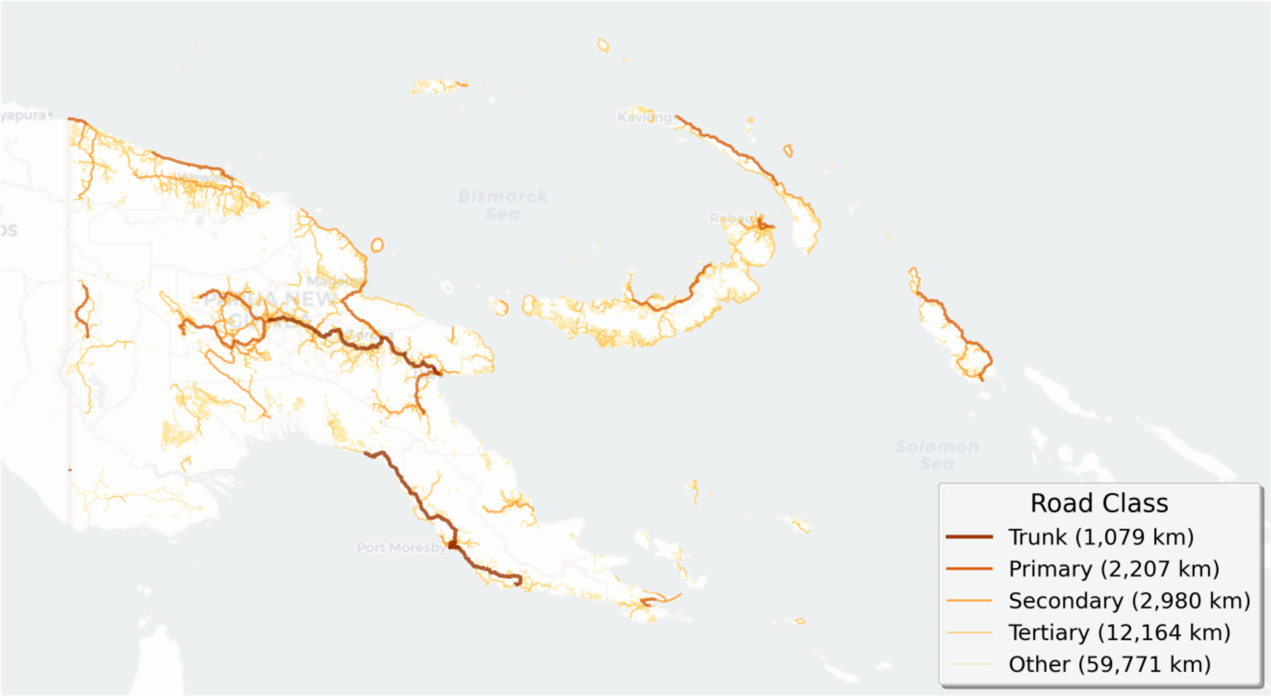
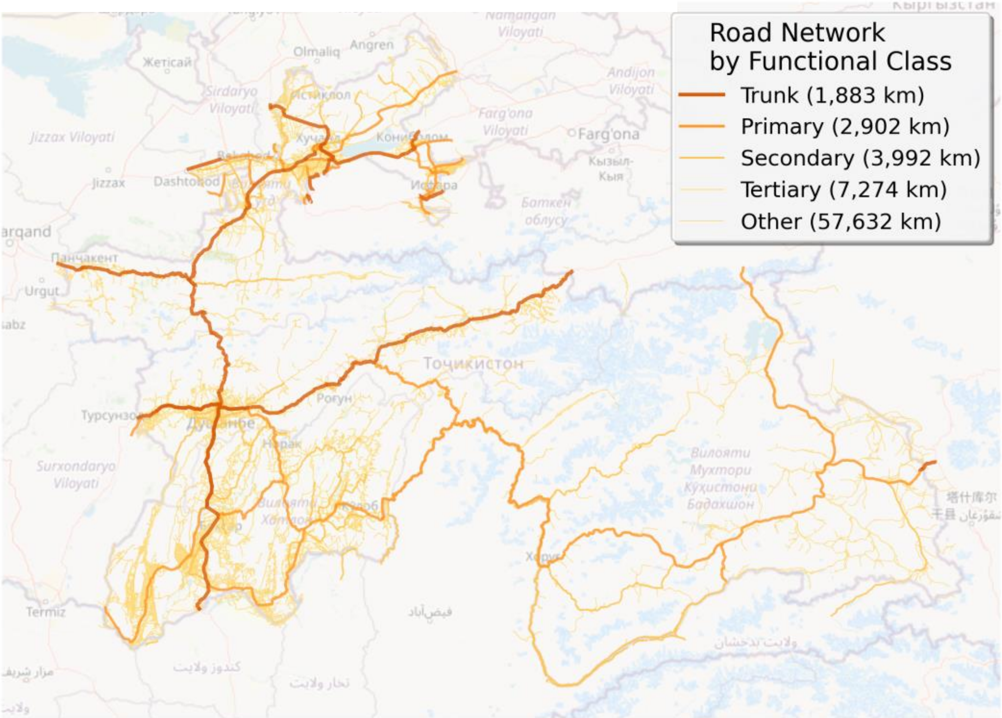
Exposure data







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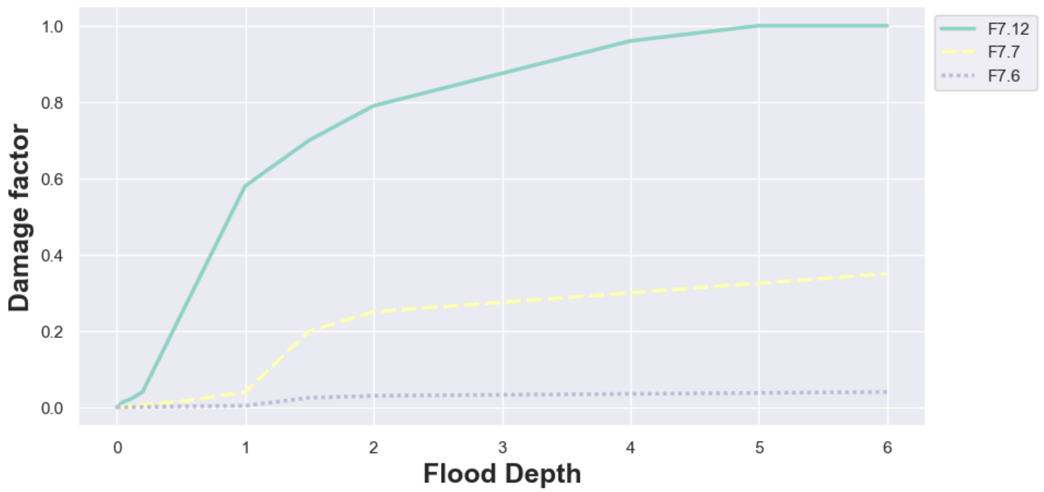
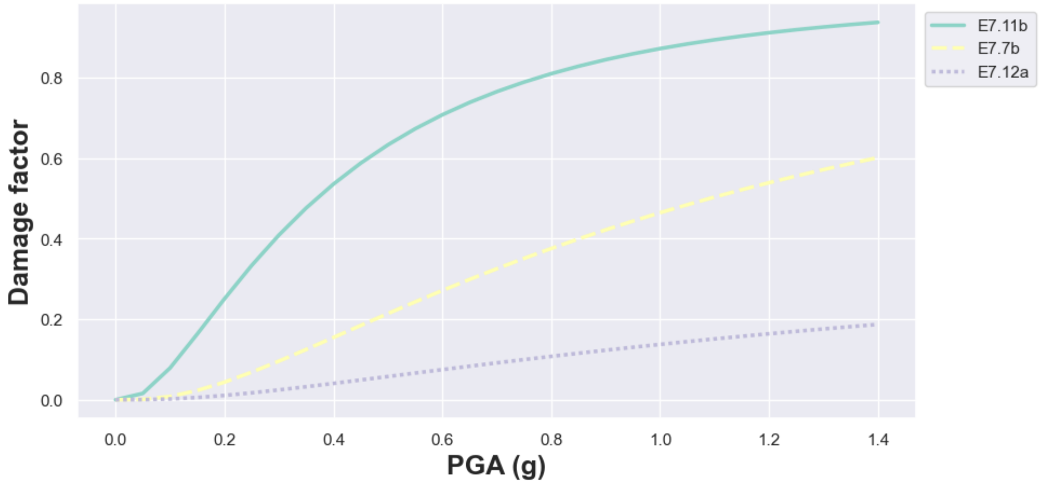
Vulnerability data

- Vulnerability curves link the intensity of the hazard to the potential damage to a specific asset
- We use our own vulnerability and fragility database as the baseline and validated the choice of the curves through national contact points where possible
- For landslide damage, we followed a similar approach as CDRI - GIRI





Review article: Physical vulnerability database for critical infrastructure hazard risk assessments – a systematic review and data collection

Sadhana Nirandjan, Elco E. Koks, Mengqi Ye, Raghav Pant, Kees C. H. Van Ginkel, Jeroen C. J. H. Aerts, and Philip J. Ward

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All through public tools

- All damage & risk assessments are performed through our open access python tool
- pip install damagescanner
- Full documentation on the website

Table of contents
- Key Features
- Background
- Quickstart
- License
- Funding

Damage Scanner

DamageScanner: direct damage assessments for natural hazards

A python toolkit for direct damage assessments for natural hazards. Even though the method is initially developed for flood damage assessments, it can calculate damages for any hazard for which you just require a vulnerability curve (i.e. a one-dimensional relation).

<u>Disclaimer for results: they are generally based on coarse assumptions and global data with large uncertainties. The results are not intended to support local/asset-specific decisions. They showcase a workflow and help to prioritize where in a country one should do further analysis.</u>

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Physical risk and heat exposure Tajikistan

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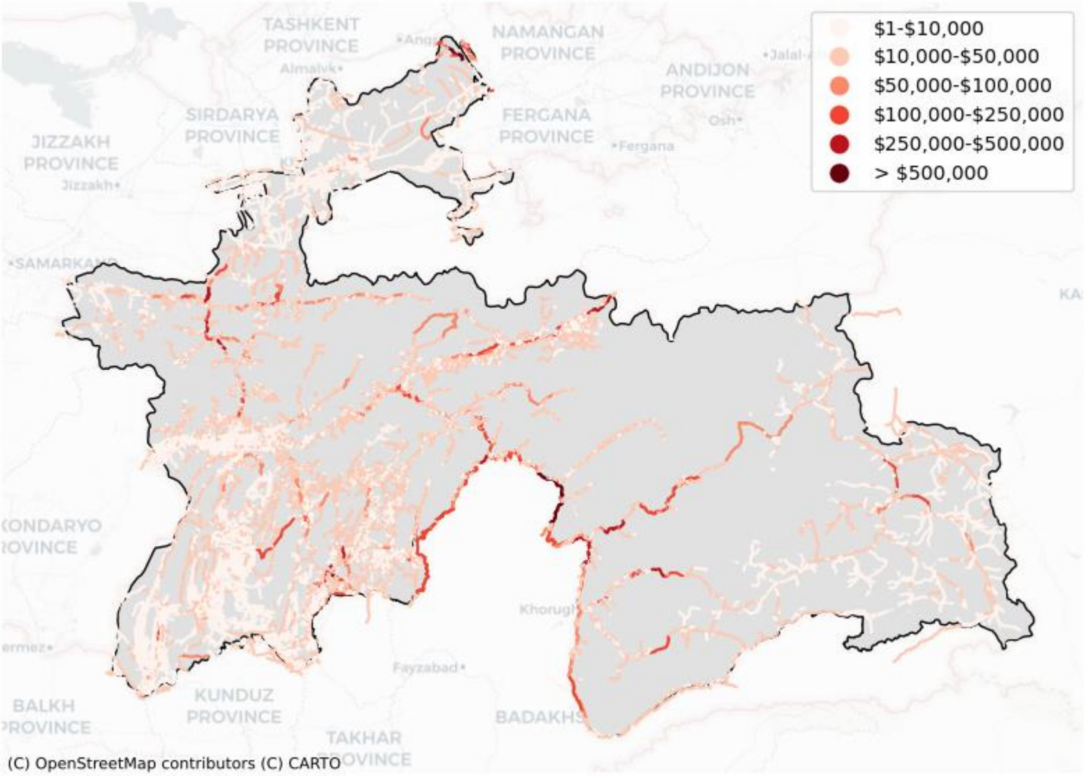

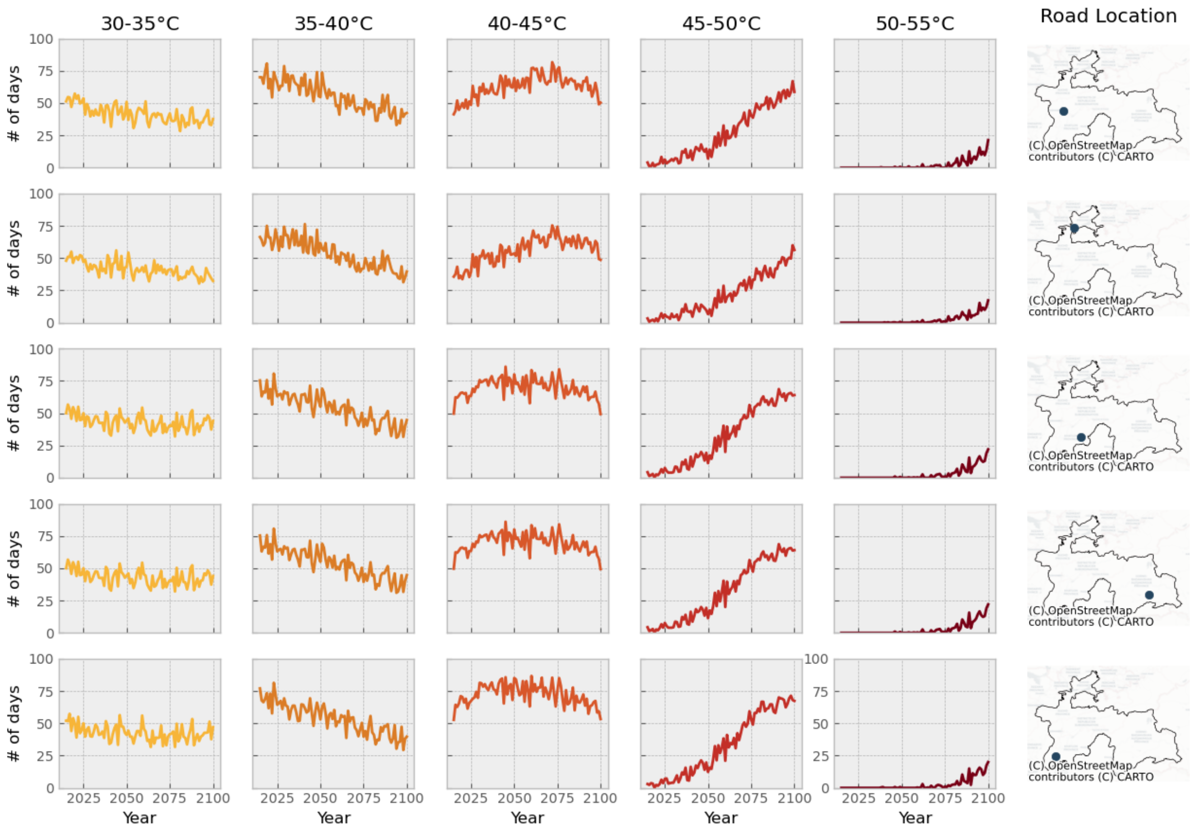

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Expected Annual Damage Pakistan

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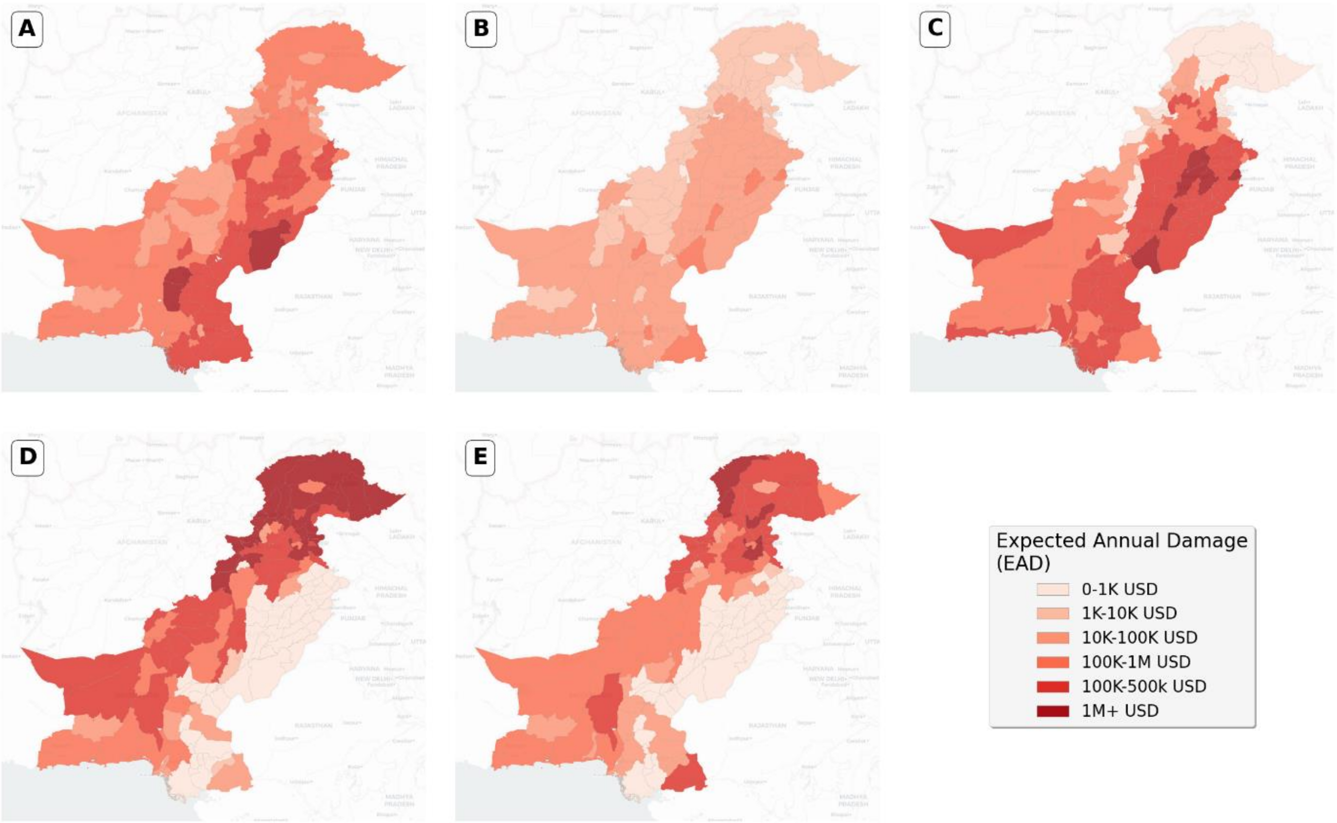
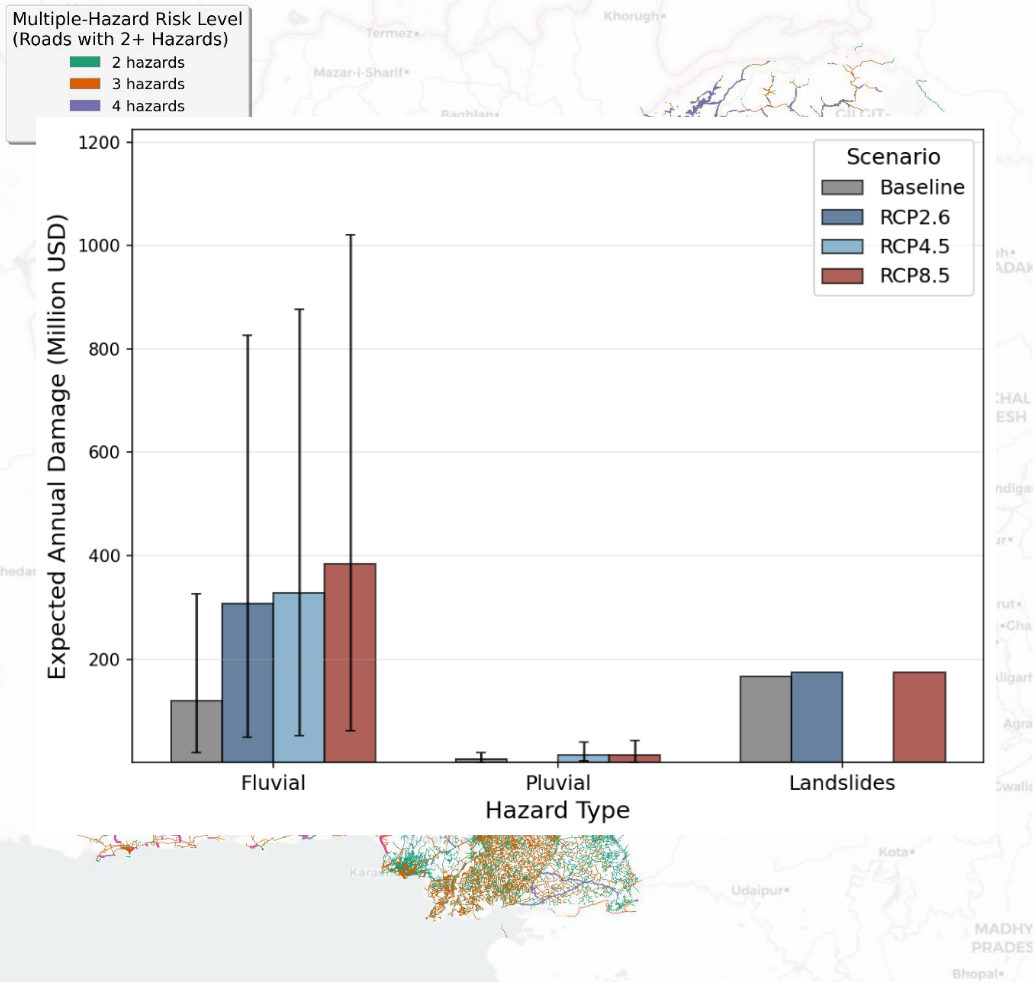
Fluvial Flooding | Pluvial Flooding | Earthquakes



EQ-landslides | RF-landslides



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Expected Annual Damage PNG

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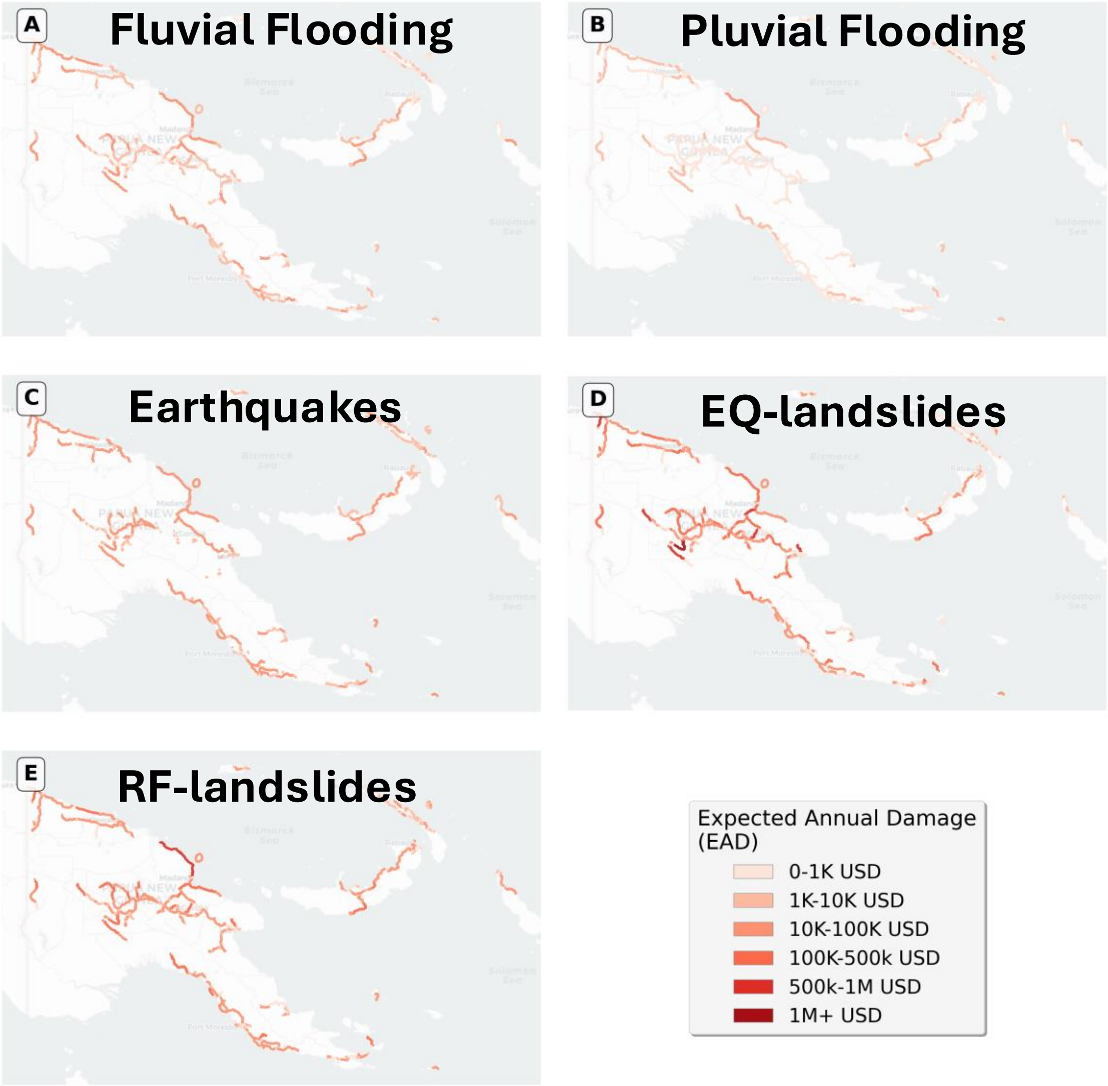

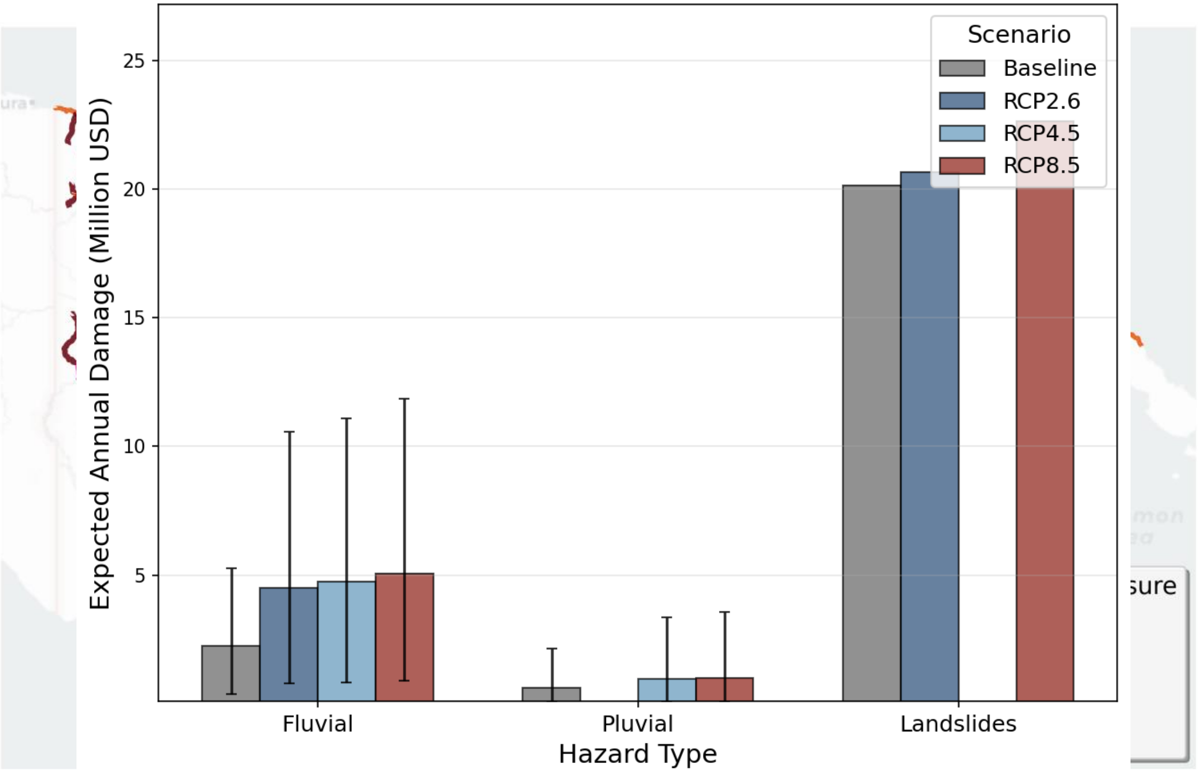

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Travel flow and accessibility losses

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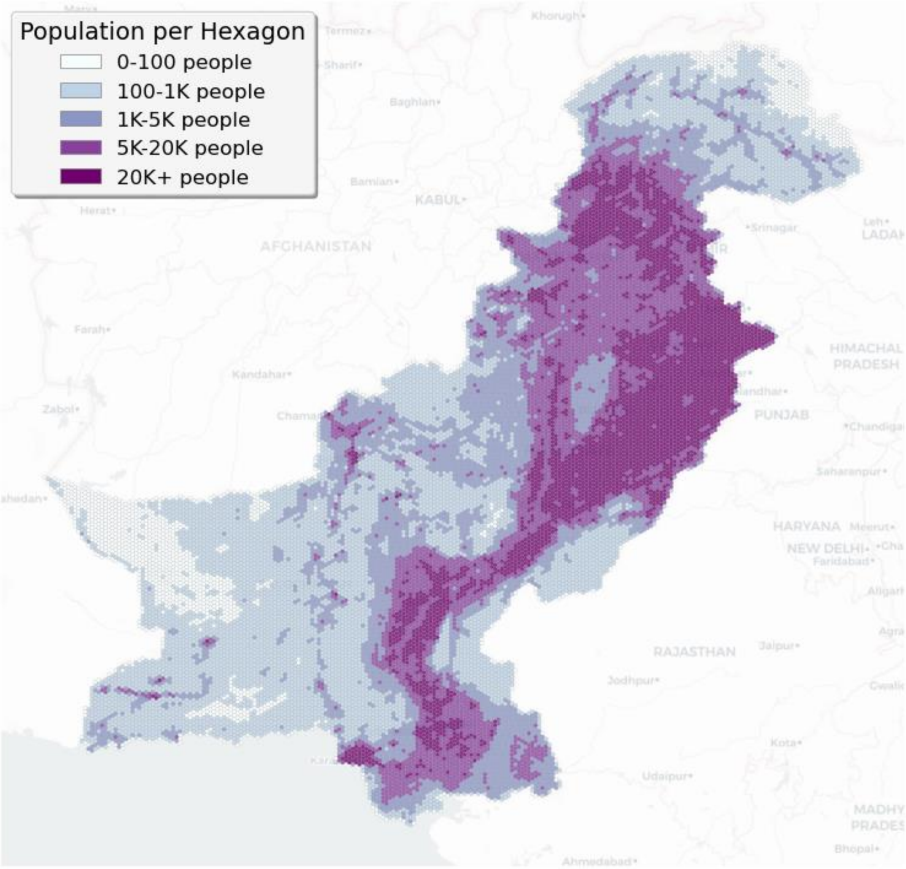
From damage to network functioning

- **Travis will dive into the details of the flow modelling**

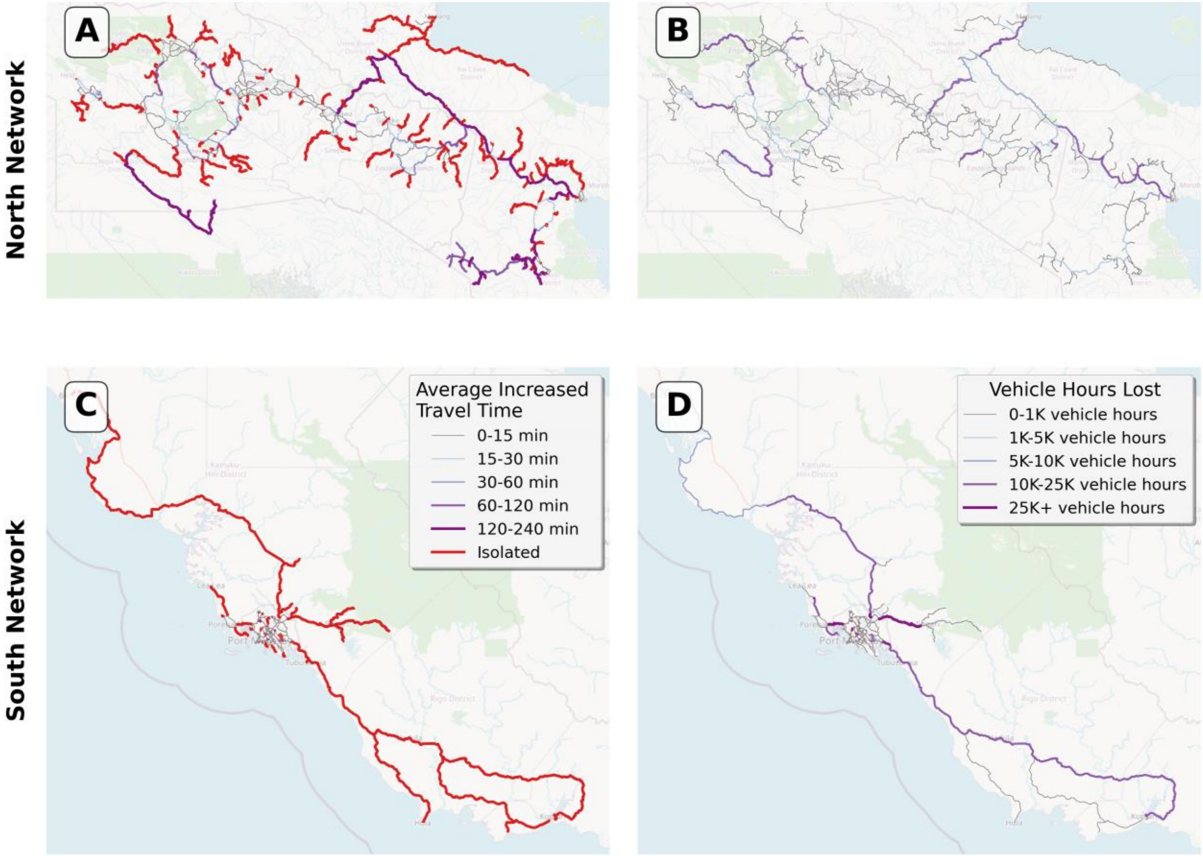
- Here I focus on the single-point of failure assessment across each country done with the data of his team -> <u>performed on the main highway network of each country</u>

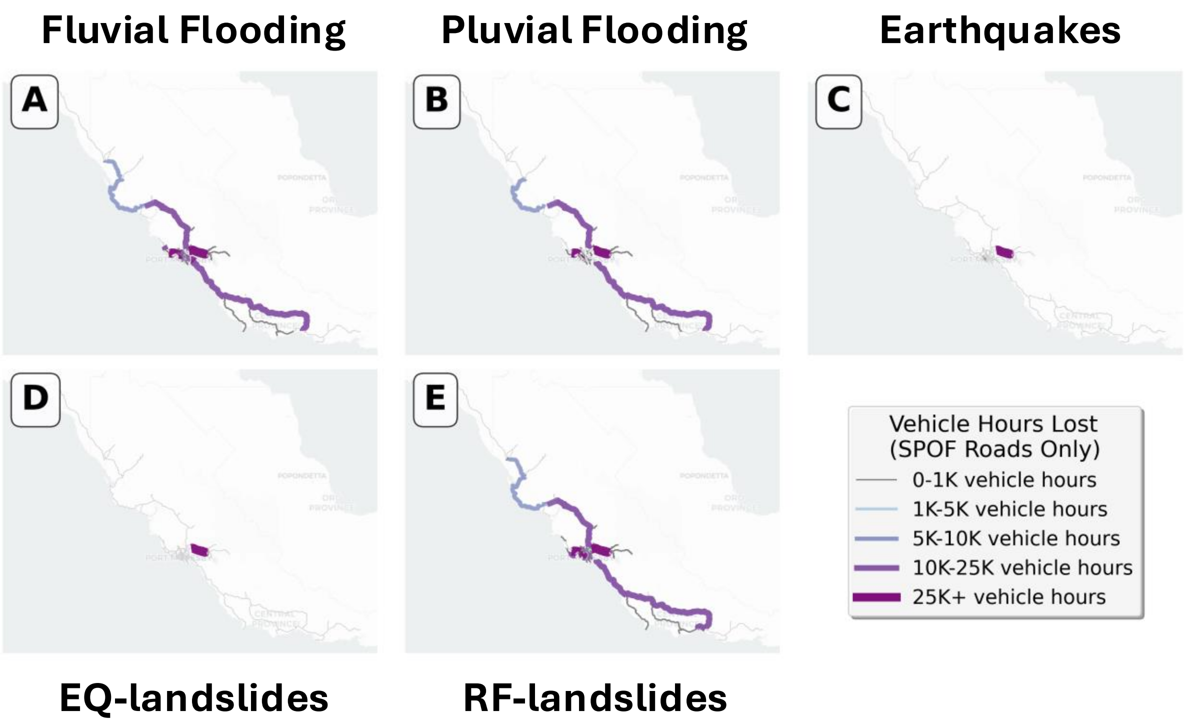
- And an accessibility assessment for healthcare facilities [and airports] due to unique river flood events.



Travel flow impacts PNG

Solving Complex Challenges Together





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Travel flow impacts Pakistan

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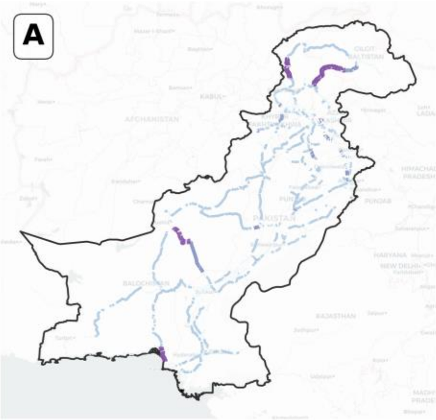
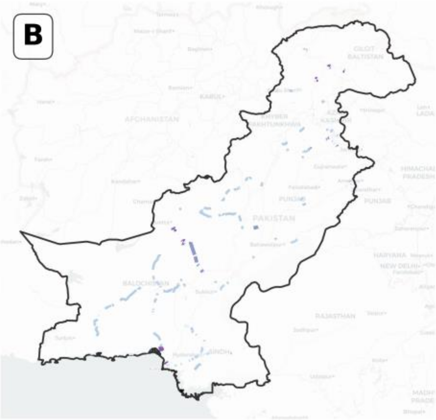
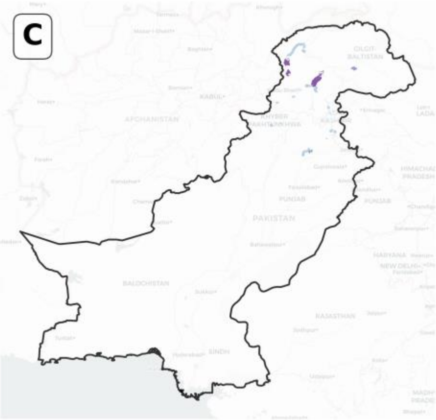
Fluvial Flooding

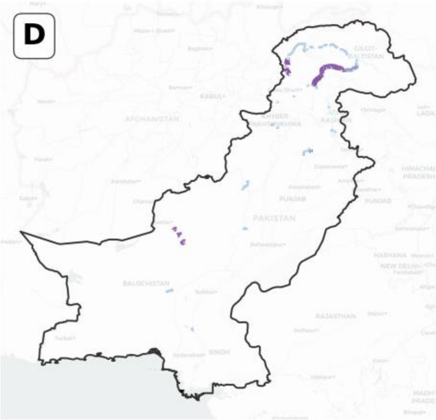


Pluvial Flooding

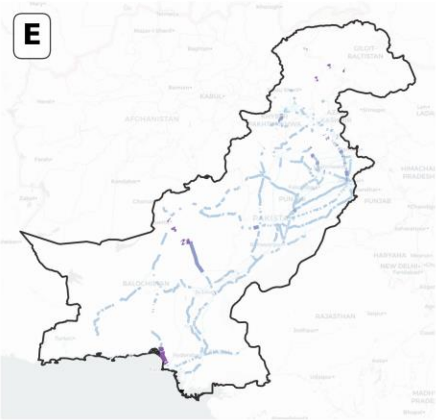


Earthquakes

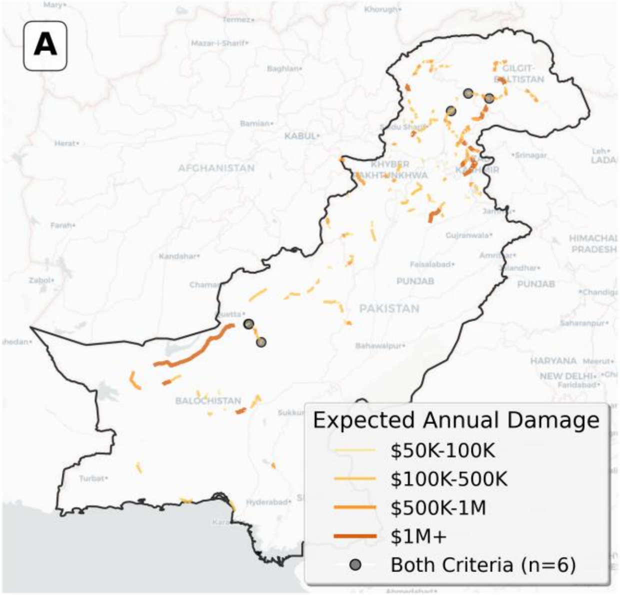


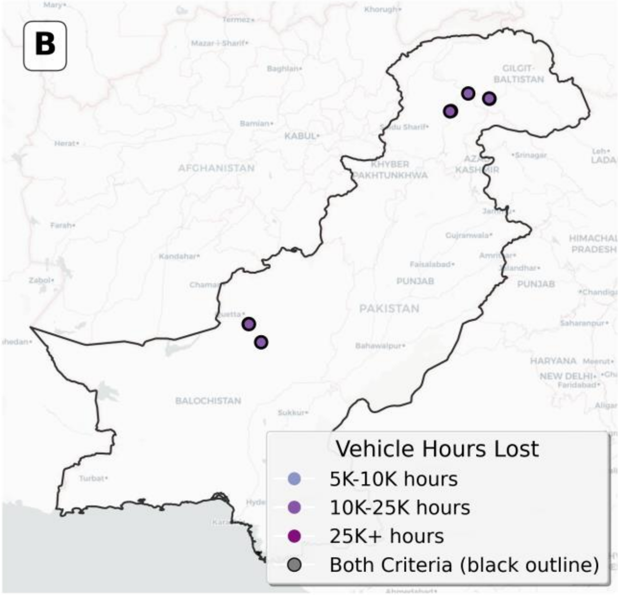


EQ-landslides



RF-landslides





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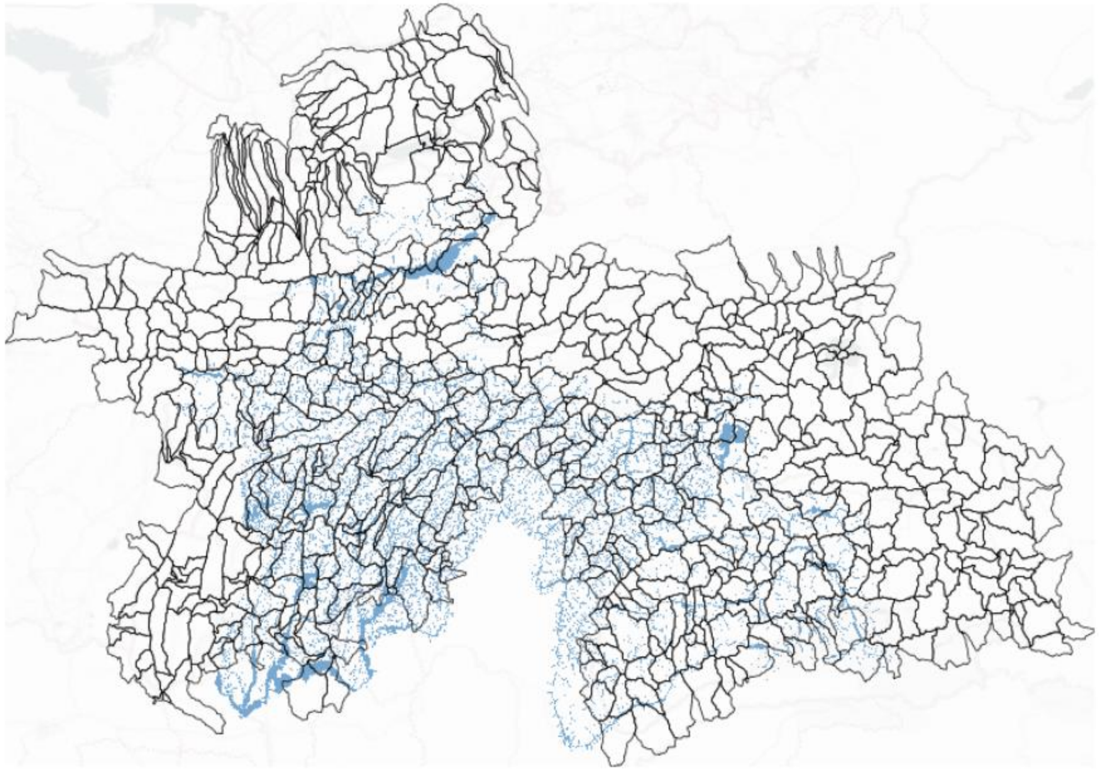
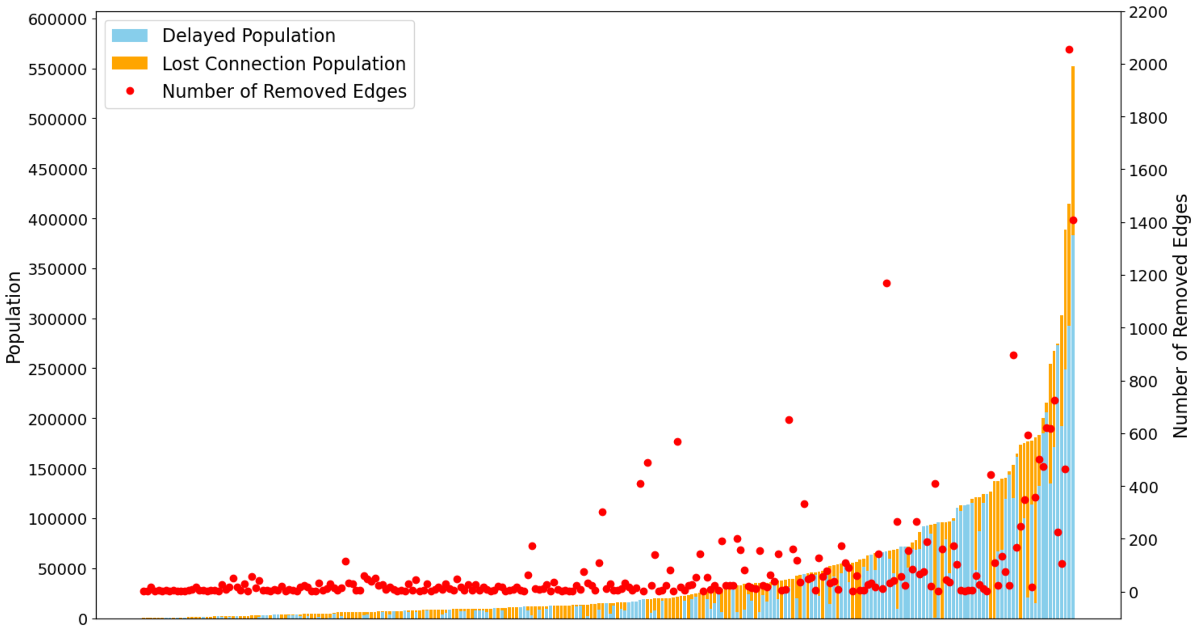
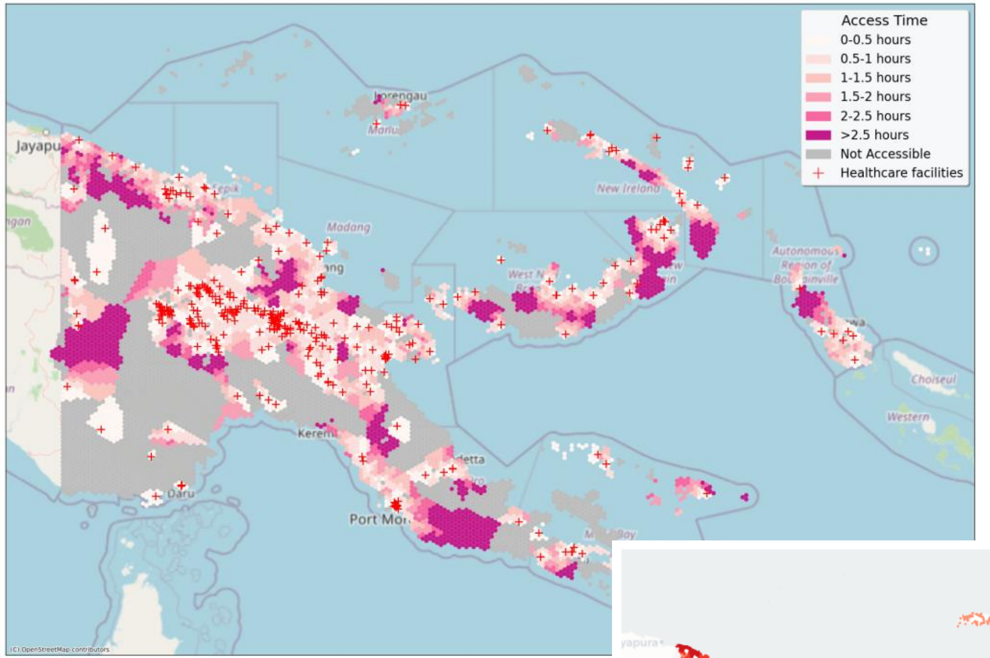
And understanding accessibility

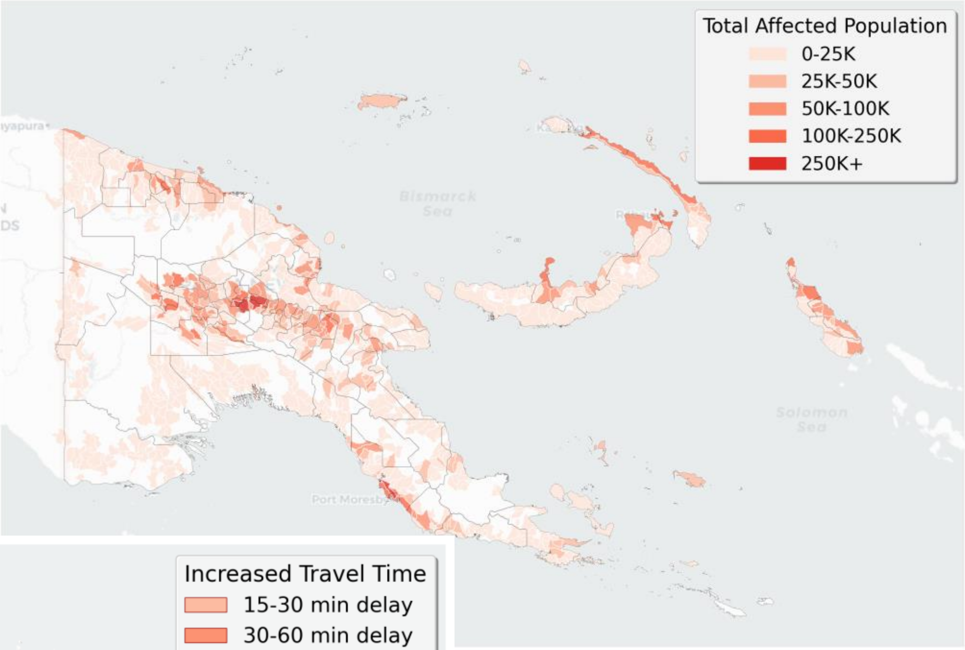


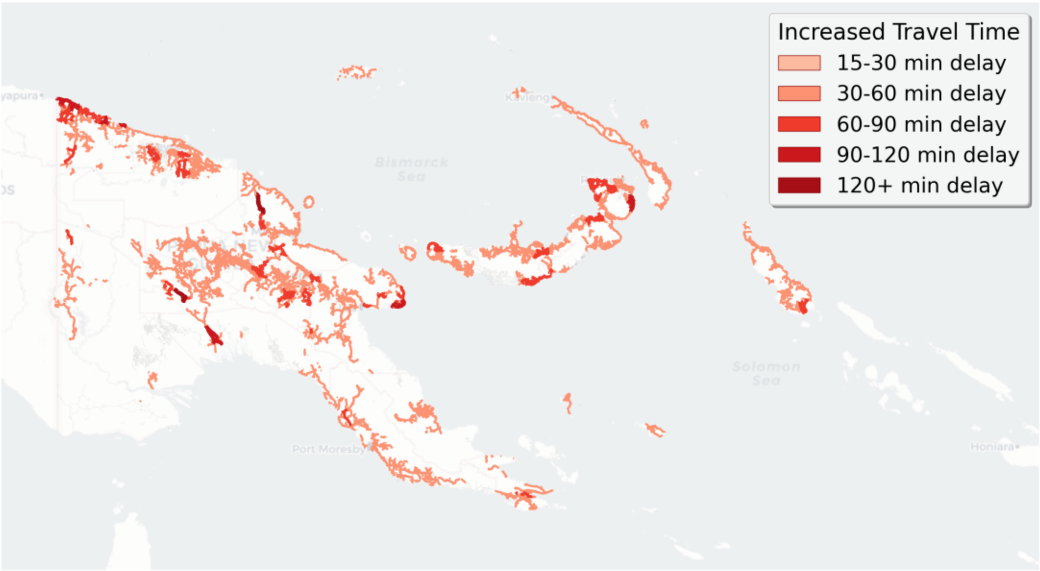
Event sets generated through assumed independency across river basins



And understanding accessibility







Moving towards climate adaptation and resilience

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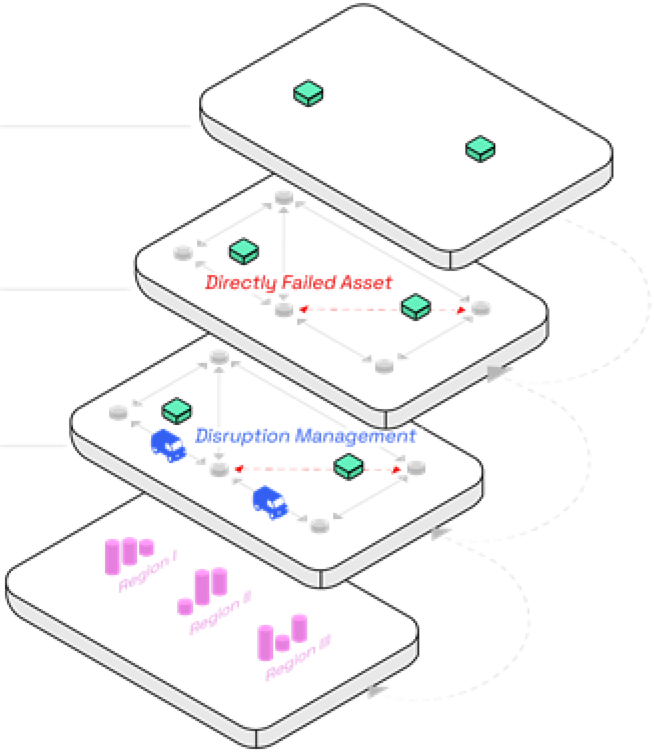
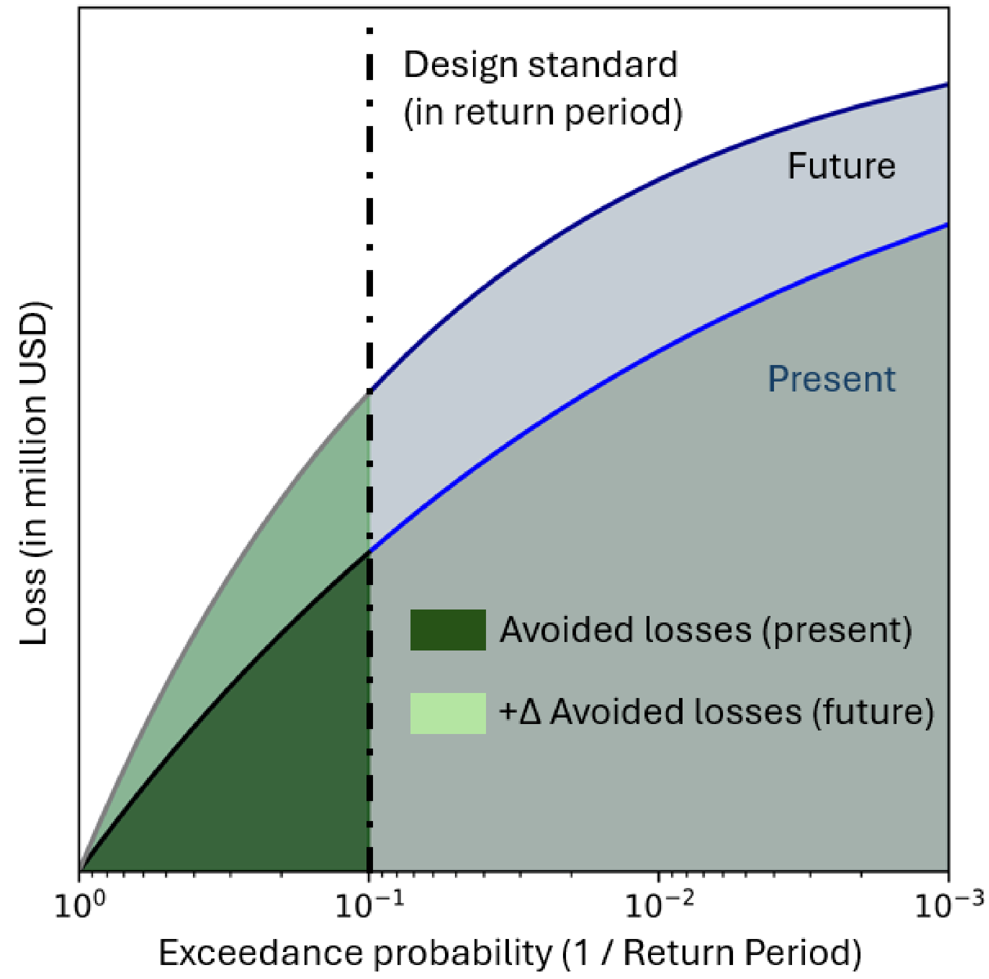
Adaptation options across levels

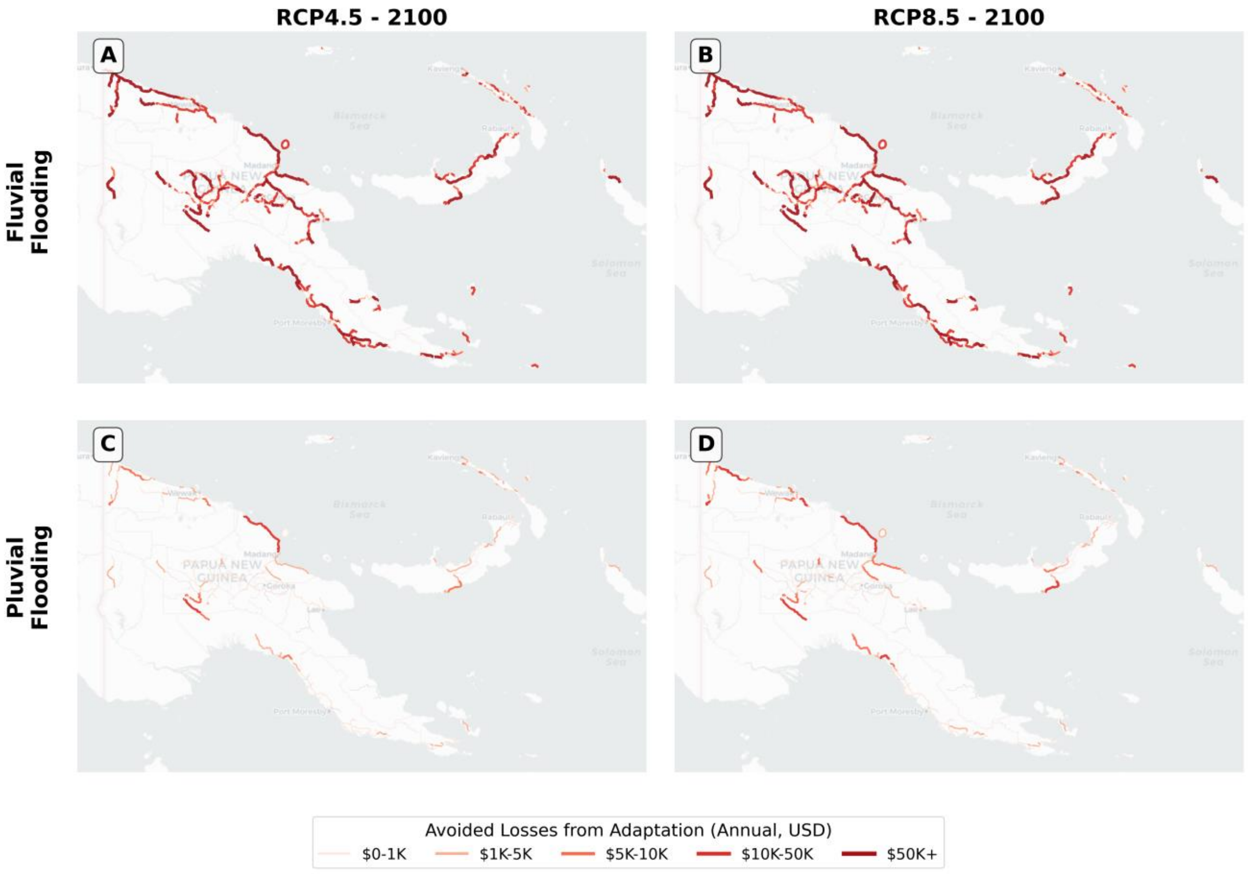
Solving Complex Challenges Together



Level	Hazard	Vulnerability	Exposure (CI)	Capacity	Supply/Demand	Recovery
Hazard-level	Building dikes and floodwalls					
Asset-level		Elevating embankments				Additional reconstruction crews
Network-level			Building new connections	Increasing freight capacity		
System-level					Increasing inventories	Recovery funds

Example: maintaining design standards





But this is just the start...

- However, key data gaps remain for the development of a proper adaptation appraisal strategy:

  - Good information on costs of various measures
  - Effectiveness of the measure (this requires, for example, more detailed knowledge of the asset)
  - Improved hazard information for climate change → still limited across a wide range of hazards for a wide range of countries [especially detailed information]

  - <u>Fillling those gaps will allow to truly compare options across multiple levels</u>

Part 2 – A deep dive into road traffic modelling within data-scarce regions for road resilience studies

Prof Travis Waller – Technische Universität Dresden

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Acknowledging the Teams for the Past Open Published Research

2003 - 2011
Univ. of Texas at Austin

2011 - 2022
UNSW, Sydney

2022 - Present
TU Dresden

Current research ongoing at TU Dresden, UNSW and the ANU.

So many amazing collaborators to acknowledge:

Approaching 50 Completed and many current PhD Students at TUD, UNSW, ANU and U. Edinburgh

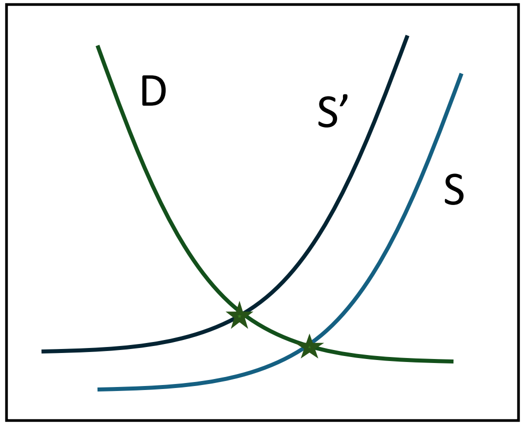
100+ Postdocs, Undergrads, MS, Colleagues

More than 40 funding sponsors including

DFG, DLR/DUT, NVIDIA, U.S. NSF, ARC, U.S. FHWA, U.S. DOT, TfNSW, Advisian, GoGet Carshare in addition to many other government agencies, software companies, infrastructure firms, advisory firms, banks, insurance companies, startups, etc.

The Need for Planning Models

- Transportation system behaviour
  - Responds non-linearly to changes
  - Is the aggregate response of thousands to millions of individuals making their own self-optimizing decisions
  - Therefore, it is traditionally represented as an equilibrium system
  - Models employ market dynamic explanations



- As a result
  - An underlying equilibrium-based mathematical model has traditionally been necessary for transportation planning and business cases
  - The global universal approach since the 1950s has been the "four step process" for transportation modelling

The four-step travel model is a ubiquitous framework for determining transportation forecasts that goes back to the 1950s. It was one of the first travel demand models that sought to link land use and behavior to inform transportation planning. (McNally, 2000)

Traditional Four-step Model for Transportation Planning

The approach is so common, there are Wikipedia pages on each step

- https://en.wikipedia.org/wiki/Trip_generation
- https://en.wikipedia.org/wiki/Trip_distribution
- https://en.wikipedia.org/wiki/Mode_choice (used when multiple modes are in scope)
- https://en.wikipedia.org/wiki/Route_assignment

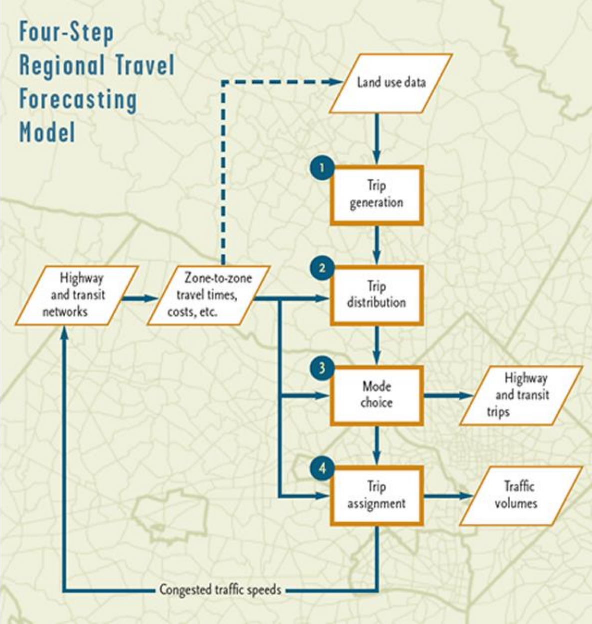


*Figure: Metropolitan Washington Council of Governments. https://www.mwcog.org/transportation/data-and-tools/modeling/four-step-model/ (Accessed April 2024)

Also https://www.transitwiki.org/TransitWiki/index.php/Four-step_travel_model (maintained by UCLA and Caltrans)

- Practically, the process often includes
  - Initial step: household travel survey
  - Physical network monitoring (roadway counts, etc)
  - Ongoing network coding and information archiving of infrastructure
  - Ongoing model calibration
- At the final step, traffic assignment, the model estimates or predicts
  - Traffic metrics (volumes, speeds, travel times)
- Because of the need for survey and ongoing monitoring
  - The overall traditional process can consume months or even years

Key Innovation for the Presented Modelling Methodology

- From pervasive data: we begin at the 4th step with traffic metrics, then use machine learning/AI to estimate the travel demand
- The relevant steps are run in reverse (without the need for surveys or ongoing network monitoring)
- Critical: We maintain the traffic assignment and trip modelling steps

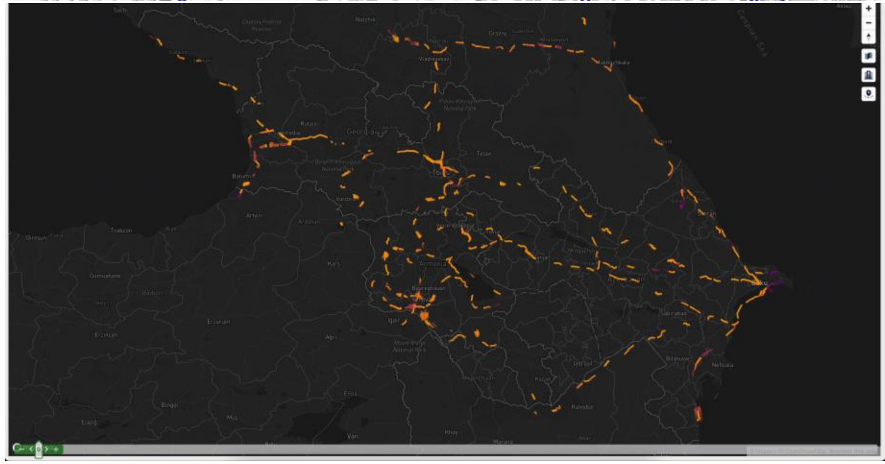
Automated Modeling for Rapid Planning

Given the importance of network demand/supply equilibrium

How can we cut the time to deploy such models?

By doing so, we create space to grow their use and usefulness

- Standardize across regions
- Increase transparency and engagement
- Incorporate novel metrics
  - Equity
  - Sustainability
  - Environmental impact/justice
  - Resilience
  - …



Critical Note:

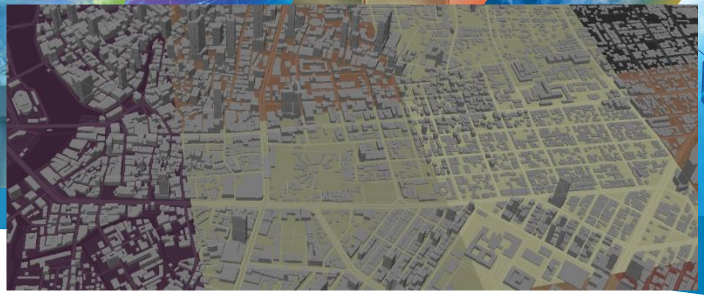
In doing all of this, we must not lose the capacity to appropriately model "what-if" scenarios.

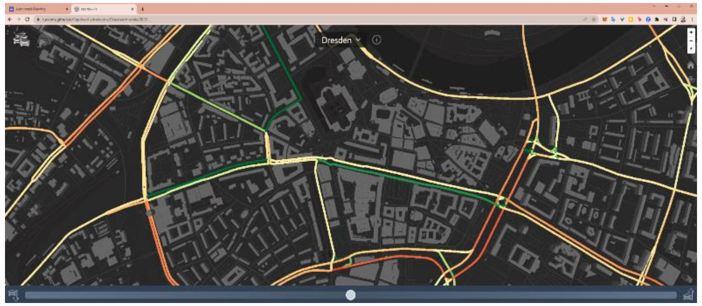
If we lose this, we lose our purpose in the planning process.

To plan is not simply to analyse. It is not just data analytics.

We would like tc
acknowledge
collaboration with
NVIDIA

Automated Modeling for Rapid Planning





- A network supply model is automatically built from OSM
- The trip estimation combines evolutionary algorithms with embedded network User Equilibrium (UE)
- Each fitness function evaluation requires UE to be solved
- Google POI and other demographic data (e.g., WorldPop) help to devise initial solutions

ST Waller, S Chand, A Zlojutro, D Nair, C Niu, J Wang, X Zhang, and VV Dixit **(2021) "Rapidex: A novel tool to estimate origin–destination trips using pervasive traffic data"** Sustainability (Switzerland), vol. 13, pp. 11171 – 11171. https://doi.org/10.3390/su132011171

D Ashmore, ST Waller, K Wijayaratna, and A Tessler **(2022) "Automated Planning For The Strategic Management of Transport Systems In Developing Countries"** Australasian Transport Research Forum Proceedings 28-30 September, Adelaide, Australia. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4191661

S Chand, ST Waller, and D Ashmore **(2022) "Building and Benchmarking Equitable Infrastructure Systems in the Wake of Rapid Urbanisation"** Policy Brief for Task Force 8: Inclusive, Resilient, and Greener Infrastructure Investment and Financing, T20 Summit, Indonesia. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4203715

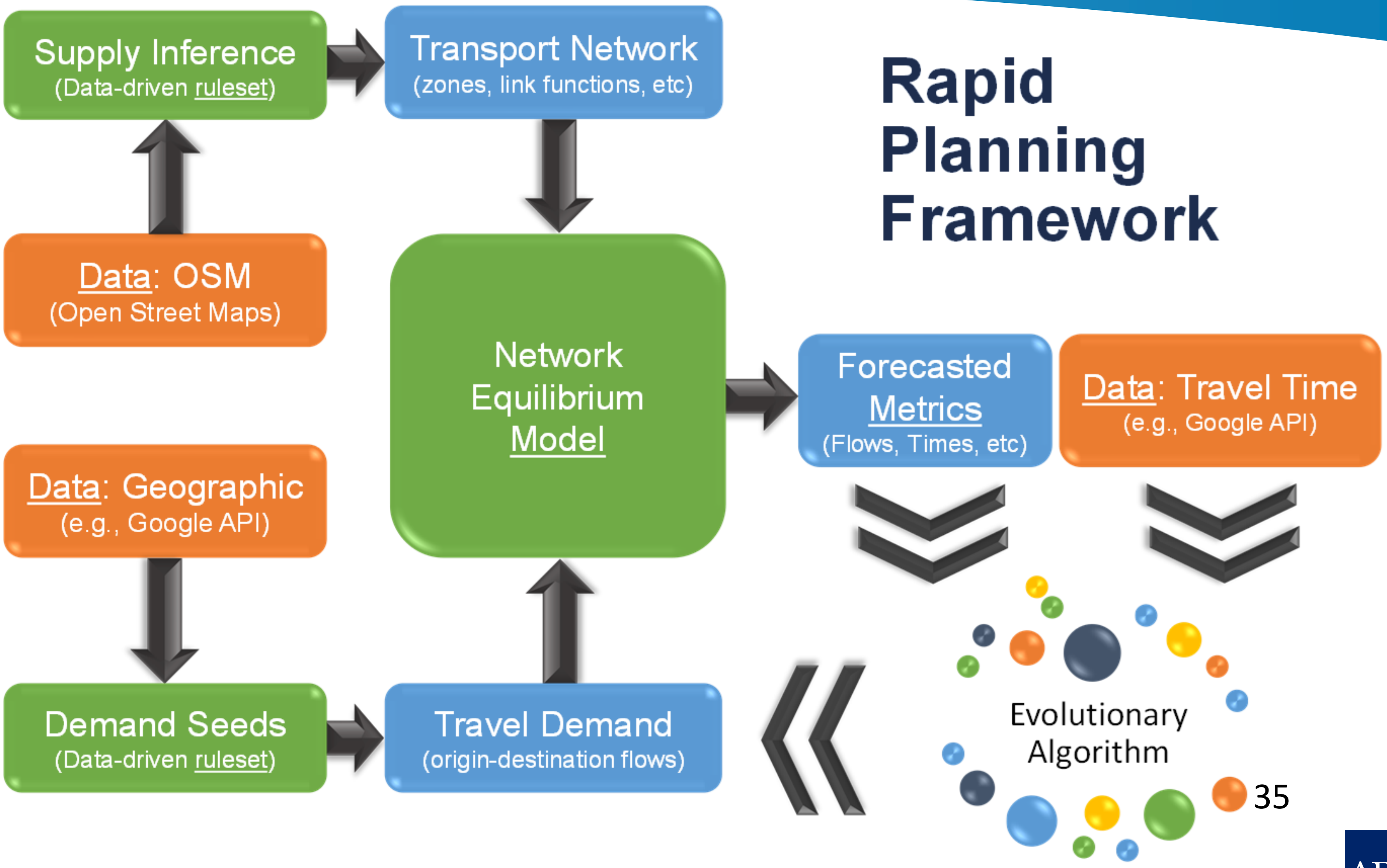
ST Waller, M Qurashi, A Sotnikova, L Karva, S Chand **(2023) "Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data"** Transportation Research Record, Volume 2677, Issue 10, https://doi.org/10.1177/03611981231161622

ST Waller, R Amrutsamanvar, M Qurashi, M Khan, S Chand, A Polydoropoulou (2025) **"Automated planning model for estimating and benchmarking road traffic carbon emissions in global cities"** Discover Cities, Vol 2, Issue 1, https://doi.org/10.1007/s44327-025-00154-3

Rapid Transport Planning: Methodological Framework

Waller et al. (2021)

- Use crowd sourced and pervasive data
- Network inference tools to automatically develop planning network from OSM and historic data on transport capacities.
- A Machine Learning, Evolutionary Algorithm, implemented to infer aggregate origin-destination travel demand forecast from observed data.



Sample of Our Past & Ongoing Evolutionary Algorithm Applications in Mobility

Traffic Signal Optimization

Sun D; Benekohal RF; Waller ST (2003) '**Multi-objective traffic signal timing optimization using non-dominated sorting genetic algorithm II**', Lecture Notes in Computer Science, vol. 2724, pp. 2420 - 2421, http://dx.doi.org/10.1007/3-540-45110-2_143

Sun D; Benekohal RF; Waller ST, 2006, '**Bi-level programming formulation and heuristic solution approach for dynamic traffic signal optimization**', Computer-Aided Civil and Infrastructure Engineering, vol. 21, pp. 321 - 333, http://dx.doi.org/10.1111/j.1467-8667.2006.00439.x

Vending Machine Allocation

Grzybowska H; Kerferd B; Gretton C; Travis Waller S (2020) '**A simulation-optimisation genetic algorithm approach to product allocation in vending machine systems**', Expert Systems with Applications, vol. 145, http://dx.doi.org/10.1016/j.eswa.2019.113110

Transport Network Design

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Tajikistan National Road Network Model

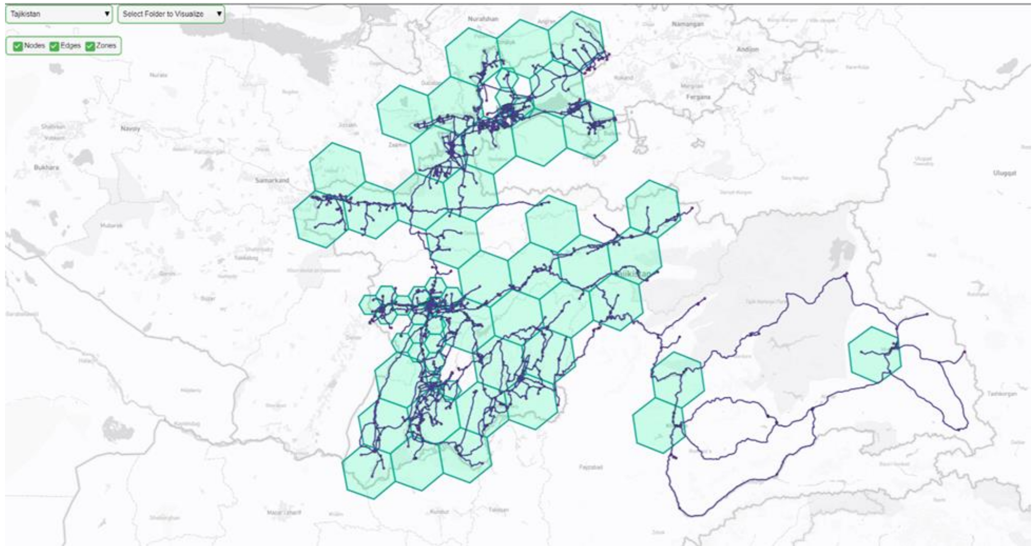
Solving Complex Challenges Together

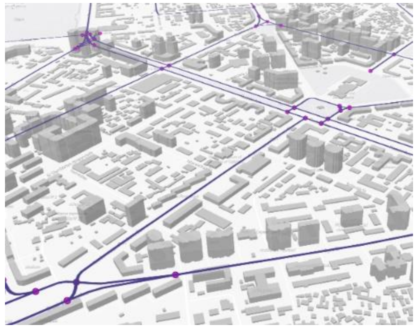
- Tajikistan Rapid Traffic Model
  - Trunk, Primary, Secondary, and Tertiary.

- Network
  - 7,660 links
  - 20,566 km roadway including
    - 2,368 km trunk roads
    - 3,787 km primary roads
    - 4,814 km secondary roads
    - 9,566 km tertiary roads.
    - 30 km uncategorized roads

- 70 Travel Zones
  - Average sizes are approximately
    - 1,770 km^2 at resolution 4
    - 253 km^2 at resolution 5
    - 36 km^2 at resolution 6

- 56,593,963 km Vehicles-Kilometers Travelled (VKT)
- 1,856,842 veh-hr Vehicle Travel Time (VTT)



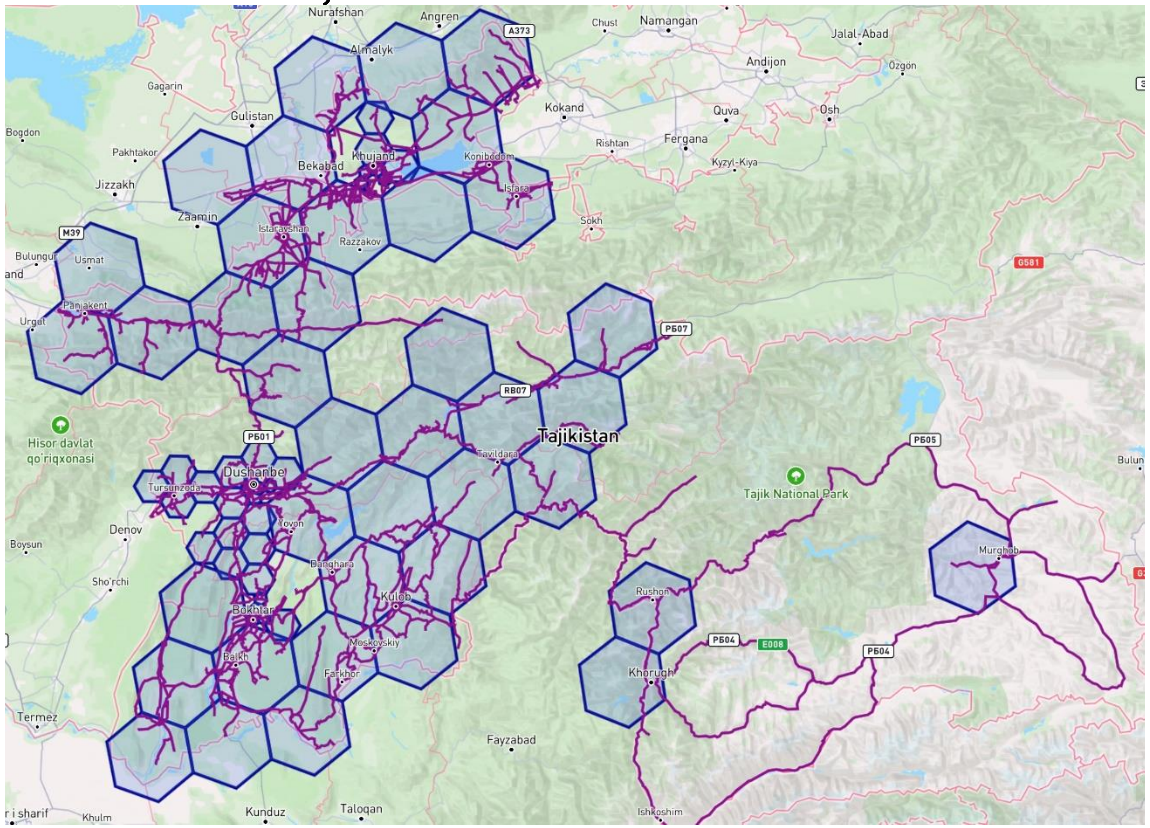


Tajikistan National Road Network Model

Solving Complex Challenges Together

National coverage spanning:
Primary, Secondary, Tertiary, and Trunk roadways

Total links: 7,660



Traffic counts available on 109 links
Count comparison available through Secondary roadways

Travel times collected from Google (midweek, morning)

Network-wide statistics comparing link counts and travel times

VKT_Estimated (for observed links)	4,499,025 km
VKT_Observed (for observed links)	4,489,053 km
Percentage .Diff	0.22 %
Percentage .Diff for Total Travel Time	6.65 %
Percentage .Diff for Total (Travel Time * distance)	0.32 %

AADT match by classification

Classification	Estimated_AADT	Observed_AADT	AADT_Percent_diff
trunk	8478	7894	7.4%
primary	4526	4591	-1.42 %
secondary	2759	3181	-13.27%

Objective: The model feeds into multi-hazard risk analysis considering environmental disruptions

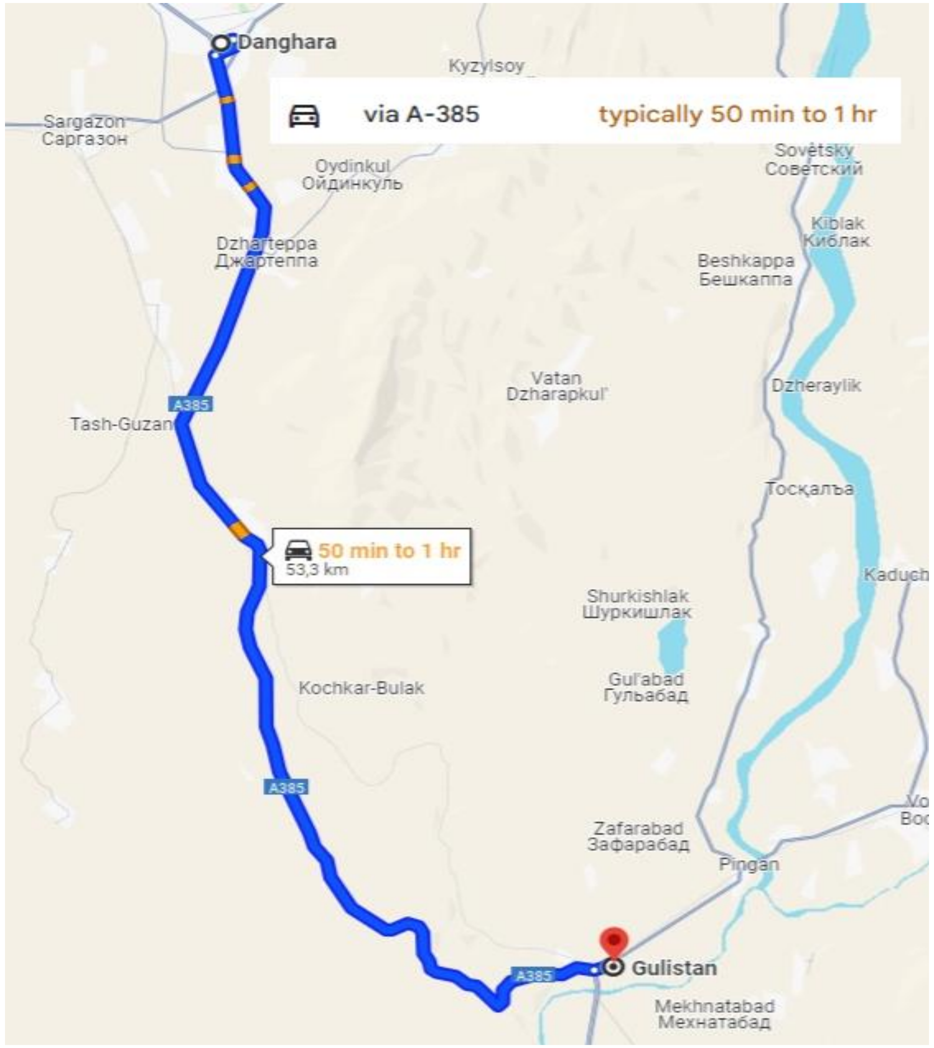
ADB

Tajikistan - Example Modelled Scenario

Solving Complex Challenges Together

- Potential closure of Dangara-Guliston Road

- Current typical Travel Time (TT), via Google, is up to approx. 1 Hour
  - Modelled travel time is 71 minutes



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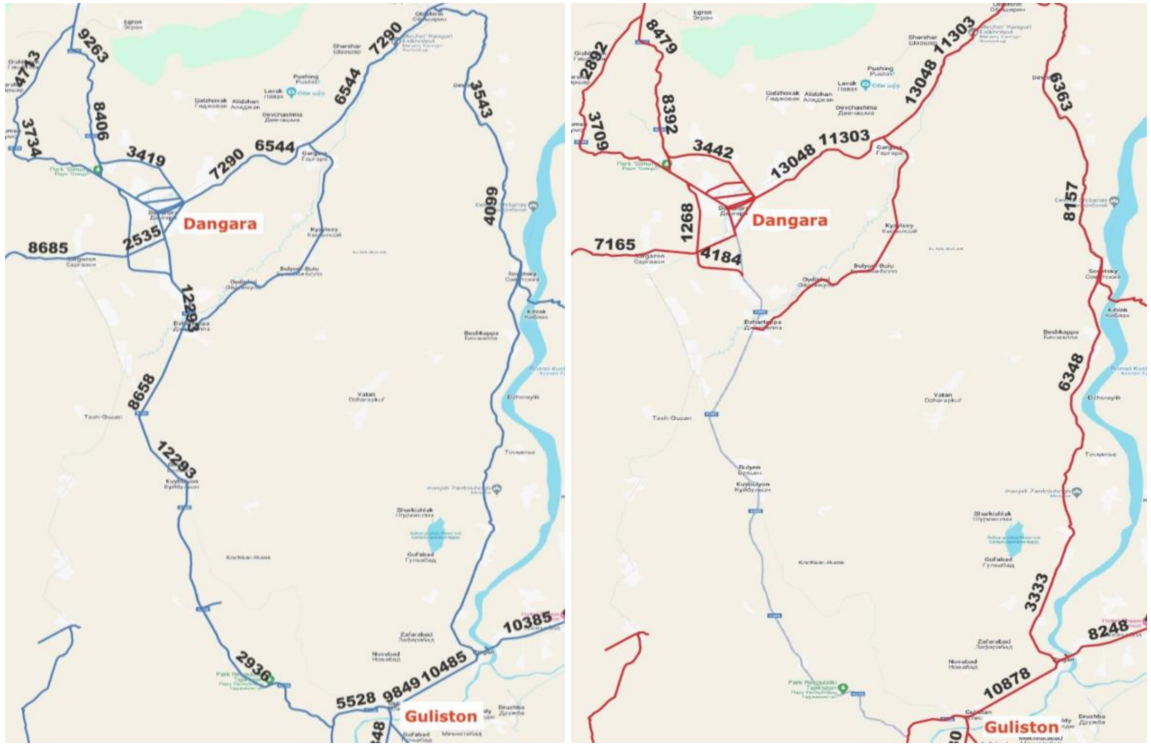
Tajikistan - Example Modelled Scenario

- Potential closure of Dangara-Guliston Road

Measure	Base Case Value	Scenario Result	Change	Change %
Vehicle Kilometers Travelled (VKT)	54,894,912 km	56,593,963 km	1,699,051 km	3.1%
Total Vehicle Travel Time (VTT)	1,856,842 veh-hr	2,022,117 veh-hr	165,276 veh-hr	8.9%
Travel Time (TT)	71 min	252 min	181 min	255%

- Analysis (comparison across full national model)



Papua New Guinea Traffic Network Models

Solving Complex Challenges Together

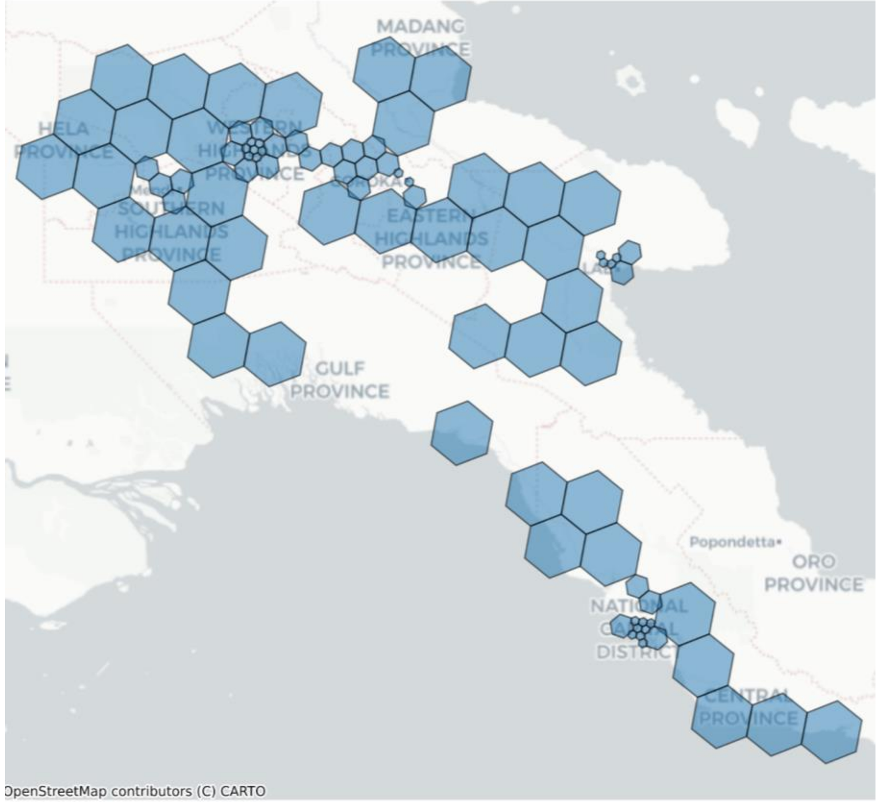
- Two base networks estimated
  - North PNG and South PNG

- 92 total zones

- Vehicle-Kilometres Travelled (VKT)
- PNG North – Network Links : 1,760
- PNG South – Network Links: 1,480

- PNG North – Total Roadway: 12,158km
- PNG South – Total Roadway: 2,394 km

- Observed AADTs: 1,622,538 km
- Modelled: 1,729,403 km



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PNG Connect Network Scenarios

Metric	Base Case (Disconnected)	No-Growth Scenario	Low-Growth Scenario	High-Growth Scenario
Link 1 AADT (Malalaua-Netindo)	0 vehicles/day	0 vehicles/day	615 vehicles/day	4,401 vehicles/day
Link 2 AADT (Kerema-Kopi)	0 vehicles/day	0 vehicles/day	862 vehicles/day	878 vehicles/day
Total System Travel Time (TSTT)	85,286 vehicle-hours	85,286 vehicle-hours	101,815 vehicle-hours	122,267 vehicle-hours

Criticality Analysis – PNG

Solving Complex Challenges Together

- North PNG
  - Network Characteristics

Metric	Value
Total segments analyzed	58
Total road length	945 km
Critical segments	8 (14%)
Non-critical segments	50 (86%)
Critical road corridors	4 (KUTUBU, ASEKI, RAMU, WAU)
Median TSTT	4.54×10^4

- Status notes how many links on the corridor would disconnect the network entirely
- KUTUBU ROAD represents the most vulnerable corridor with both direction segments showing extreme criticality

Criticality of Disconnecting Roads

Road	Disconnecting Segment percentage	Critical Section length	Status
ASEKI ROAD	50%	68.08 km one direction	2 disconnecting, 2 non-disconnecting
RAMU HIGHWAY	~34%	5.53 km each direction	2 disconnecting, 6 non-disconnecting
WAU ROAD	~34%	8.8 km each direction	2 disconnecting, 6 non-disconnecting
KUTUBU ROAD	100%	93.39 km each direction	2 disconnecting

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Criticality Analysis – PNG

- The HIGHLANDS HIGHWAY shows variable impact across its length
  - with most sections having efficient alternatives (0-2% increase) and
  - two segments showing 104.8% TSTT increases indicating longer detours.
- Four corridors (KUTUBU, KARAMUI, ATIRIGU, UNGAI SIANE) show TSTT at baseline
  - Indicates these roads carry minimal traffic in the current network, so their closure produces minimal measurable system-wide impact.

Criticality of Non-Disconnecting North PNG Roads

Road	Segments	TSTT Range	Max Impact
HIGHLANDS HIGHWAY	12	4.53×10^4- 9.28×10^4	104.8% increase
BUNDI HIGHWAY	10	4.56×10^4- 5.28×10^4	16.5% increase
KARAMUI ACCESS	8	4.53×10^4	0% (low traffic)
KOROBA ROAD	2	4.54×10^4	0.22% increase
ATIRIGU ROAD	2	4.53×10^4- 4.54×10^4	0.26% (low traffic)
UNGAI SIANE ROAD	2	4.53×10^4	0.14% (low traffic)

- More limited South PNG Network
  - SOGERI ROAD represents the most critical identified vulnerability in this network.
    - SOGERI ROAD connects Port Moresby to the Sogeri Plateau and communities beyond.

Conclusions

ADB

Solving Complex
Challenges Together

Conclusions & steps forward

Solving Complex Challenges Together

- Here, we presented a resilience workflow which can be applied globally → every bit of extra local information will reduce the uncertainty in the results.

- The process combines multi-hazard analysis with traffic equilibrium modelling leveraging open data sets and emerging techniques

- Final reports will be converted into an ADB publication

- Moreover, methods and approaches will be submitted as academic publications

Questions?

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