# Overview of Resilient Systems

*2021 APRU Multi-Hazards Summer Lecture Series: Creating a Resilient Society against Multiple Hazards*

28 July 2021

Dr Jonas Joerin
Co-Director, Future Resilient Systems, Singapore-ETH Centre

CREATE ETH zürich NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE NUS STEVENS ILLINOIS

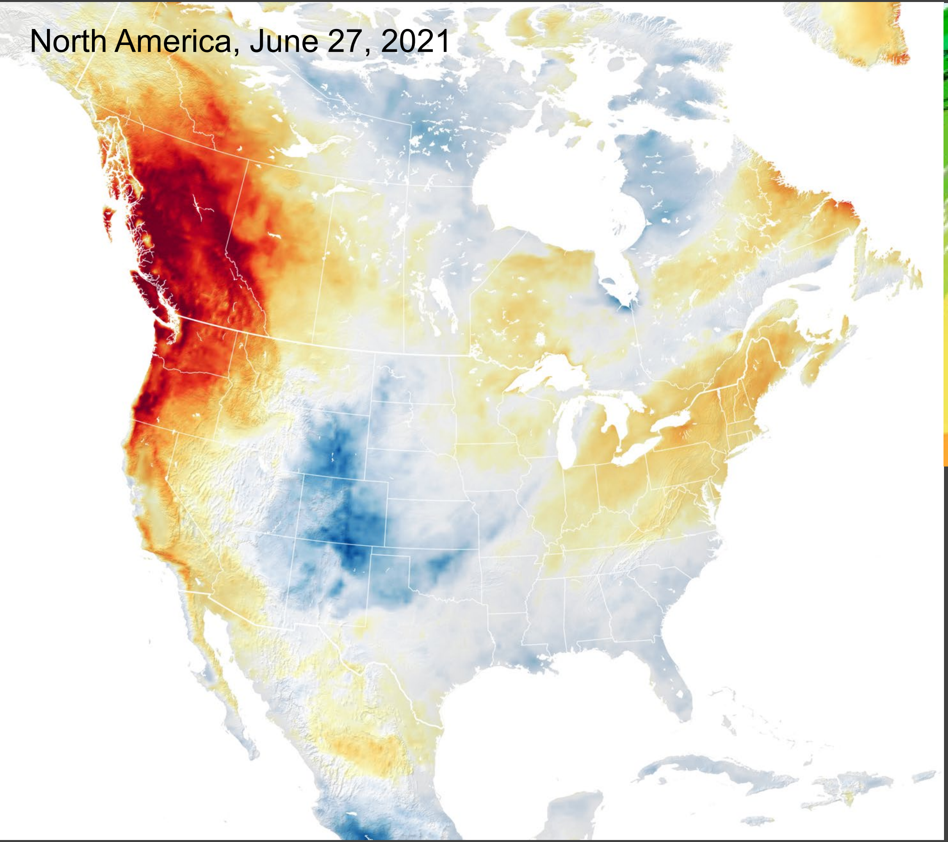
(FRS) FUTURE RESILIENT SYSTEMS

# Poll

# Outline

- Recent extreme events in North America and Europe
- Worldwide trend of disasters
- Changes in global risk perception
- Risk analysis framework
- Rising protection gap and increasing risk
- What is resilience?
- Regime shifts
- Applications of the concept of resilience:
  - Critical infrastructure systems resilience
  - Food system resilience
  - Social resilience
  - Socio-technical resilience
- Smart cities and resilient systems
- Summary

# 2021 Western North America Heat Wave – Extreme Event




Source: NASA Earth Observatory/Joshua Steven

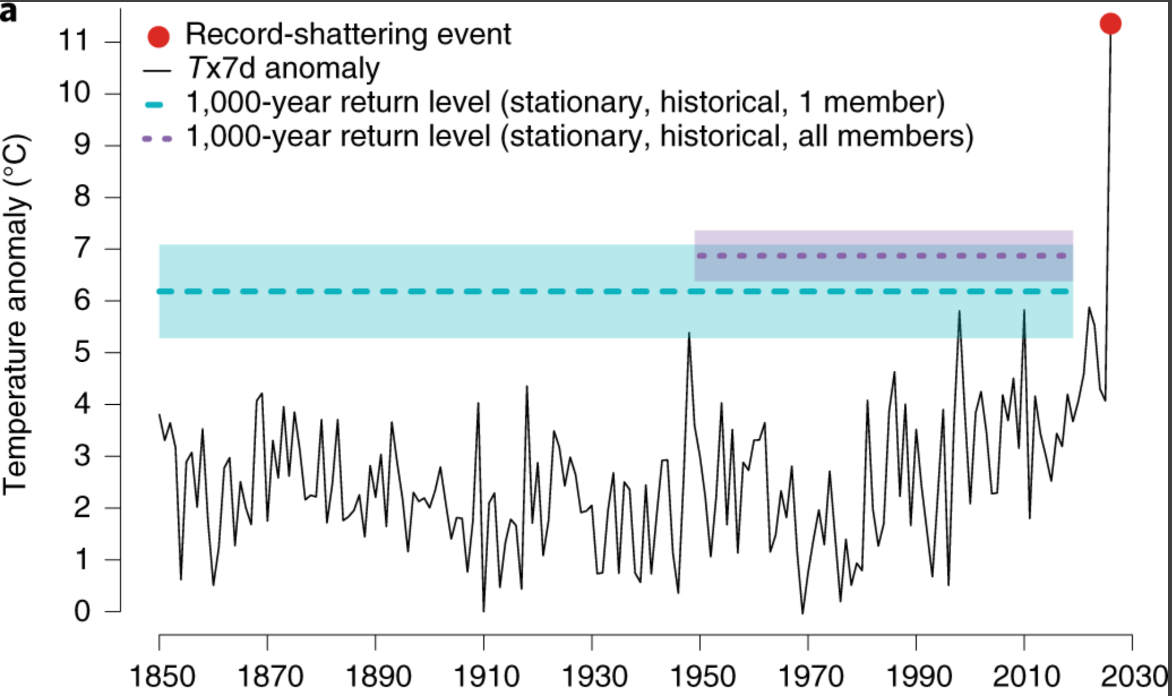

What happened:

- High pressure area was sandwiched between two low pressure areas
- Anomalies relative to average daily temperatures (2014-2020) were up to 15°C higher for the same day

Losses:

- > 900 deaths, wildfires
- > USD 3 billion

# 2021 Western North America Heat Wave – Past Heat Wave Events in North America




Key observations:

- Likely amplified by climate change (Philip et al., 2021; Fischer et al., 2021)
- Potentially a 'Grey Swan' event – an event that would not be predicted based on history, but may be foreseeable using physical knowledge together with historical data (Lin et al, 2016).

Fischer, E.M., Sippel, S., & Knutti, R. (2021). Increasing probability of record-shattering climate extremes. Nature Climate Change, in press

# 2021 European Floods – Extreme Event


Erftstadt, July 2021
Source: Rhein-Erft-Kreis/dpa/picture alliance/

## What happened:

- A storm complex moved from France to Germany and brought excessive amount of rainfall

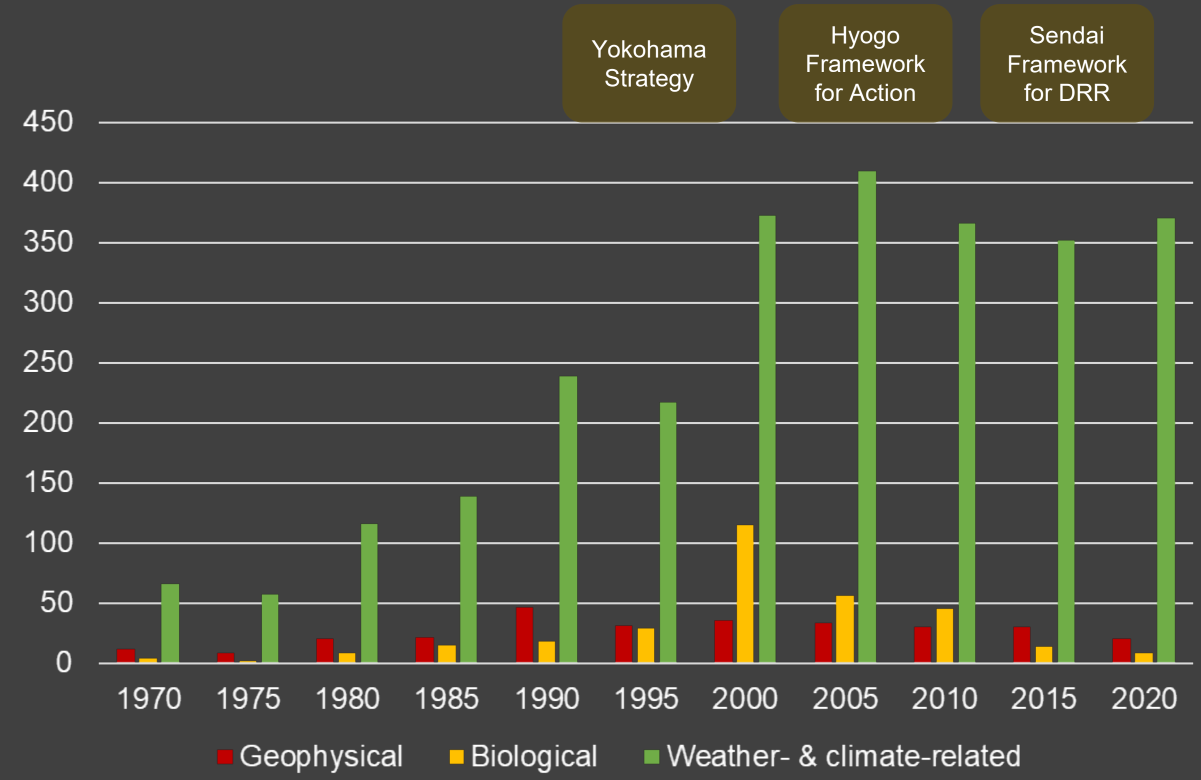
## Losses:

- > 200 deaths
- > USD 3 billion

## Key observations:

- Intense rainfall was forecasted for affected areas
- Not a Grey or Black Swan event

# Number of Disasters – Worldwide



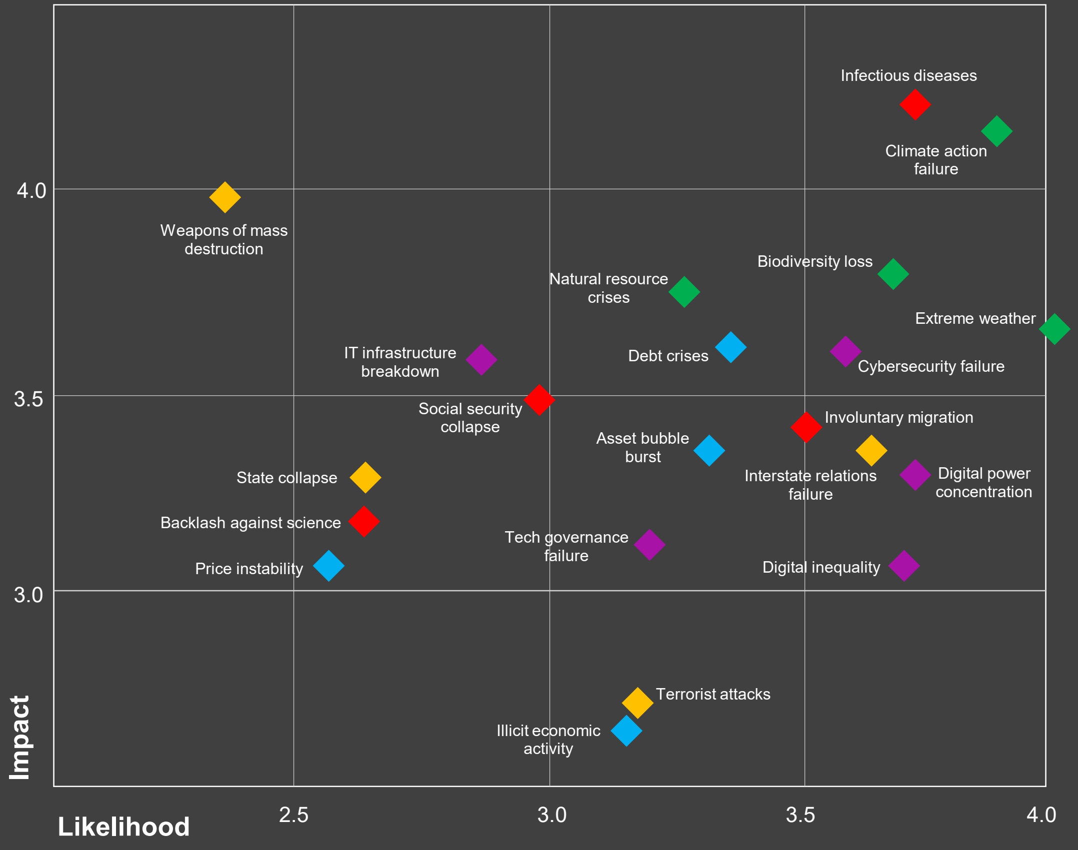

Trend:

- Number of weather-related disasters stabilised during the last two decades

Source: EM-DAT, CRED, 2021

(FRS) FUTURE RESILIENT SYSTEMS

# Global Risks in 2020



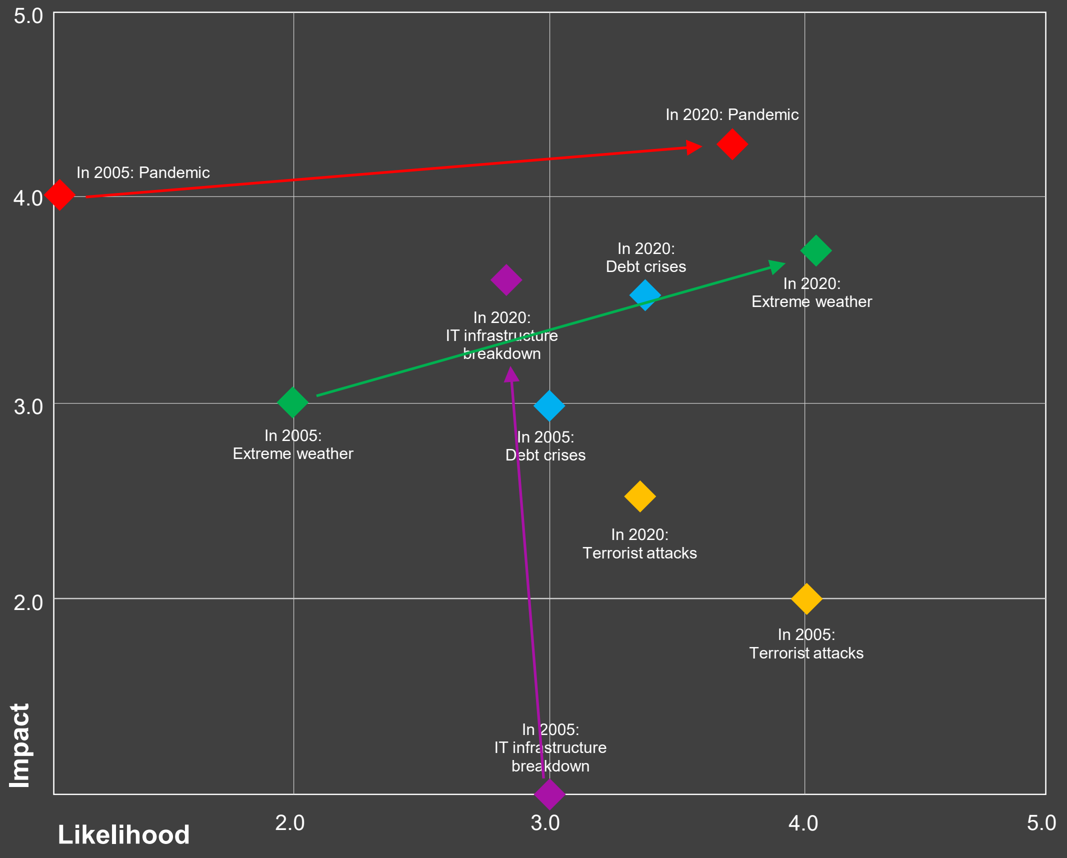

Source: The Global Risks Report 2021, 16th Edition, World Economic Forum

Experts from various sectors and disciplines provided their perception on the potential **likelihood** and **impact** of key risks for the global level.



(FRS) FUTURE RESILIENT SYSTEMS

# Global Risks: Changes from 2005 to 2020

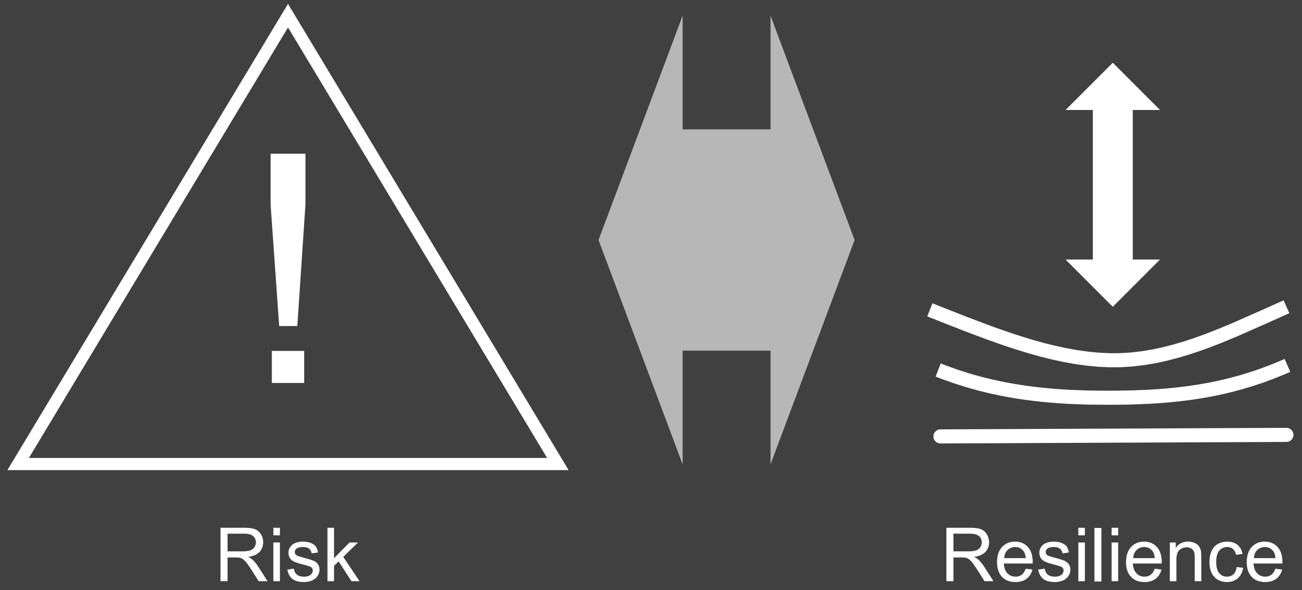



Source: The Global Risks Report 2021, 16th Edition & Global Risks 2006, World Economic Forum

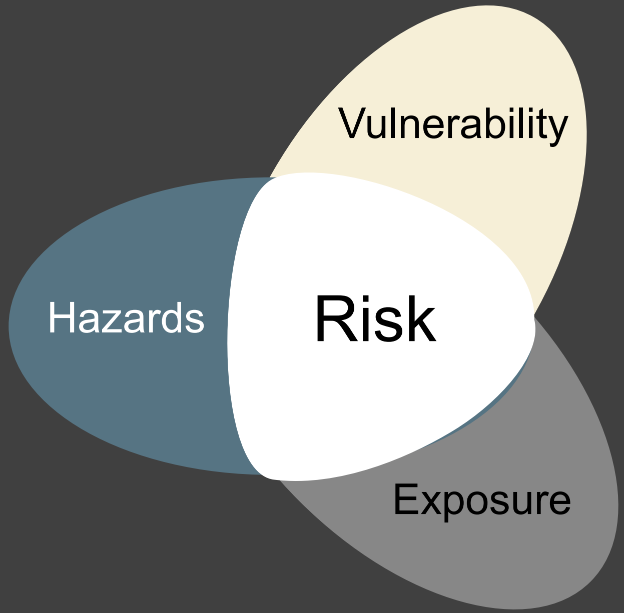
## Key changes:

- Pandemics and extreme weather more likely to occur with similar intensity
- Increasing digitalisation and global interconnectedness leads to higher impacts in case of IT breakdown

# From Risk to Resilience



# Risk Analysis Framework




A few definitions…

Risk is typically defined as:
Risk = Hazard x Exposure x Vulnerability

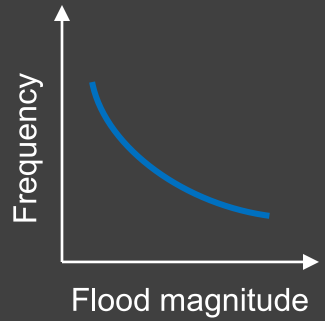
Hazard: a potentially **destructive physical phenomenon** (e.g., an earthquake, a windstorm, a flood).

Exposure: the **location**, **attributes**, and **value of assets** that are important to communities (people, buildings, factories, farmland, etc.) and that could be affected by a hazard.

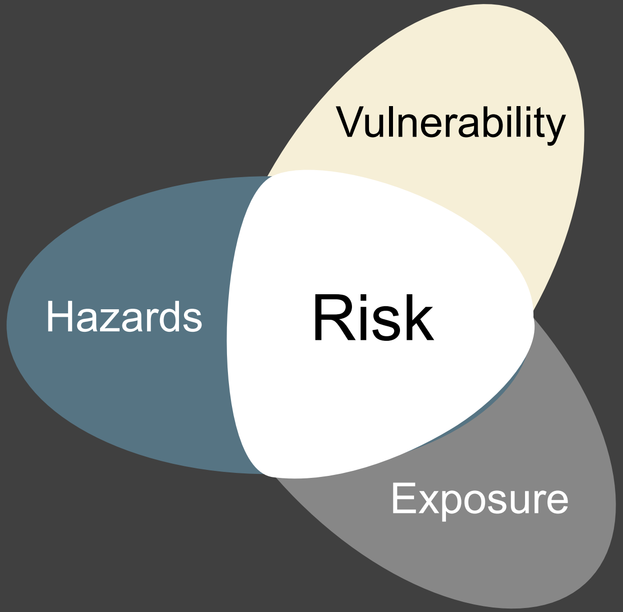
Vulnerability: the **likelihood** that assets will be damaged/destroyed/affected when exposed to a hazard

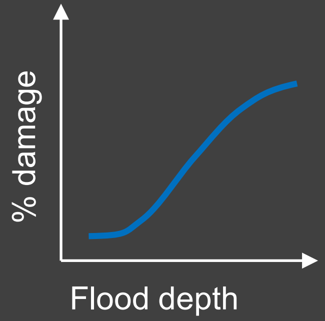
Source: https://understandrisk.org/vizrisk/what-is-risk/

# Risk Analysis Framework – Drivers in the Context of Flood Hazards




Climate change



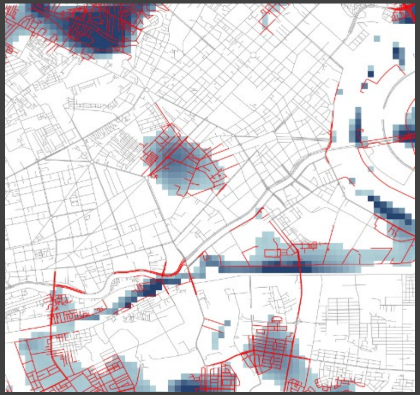

Unplanned development

Soil condition

…

Human-environmental coupling

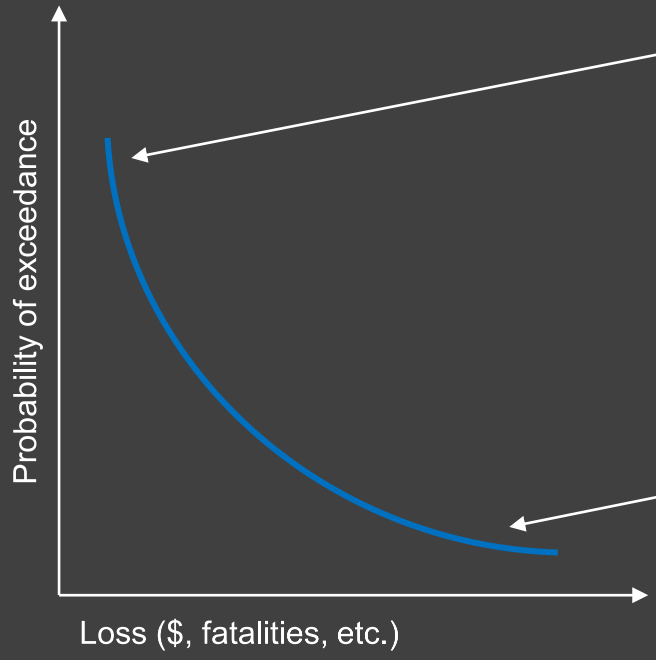
Flood hazard map from Ho Chi Minh City, FATHOM 2



Urbanisation

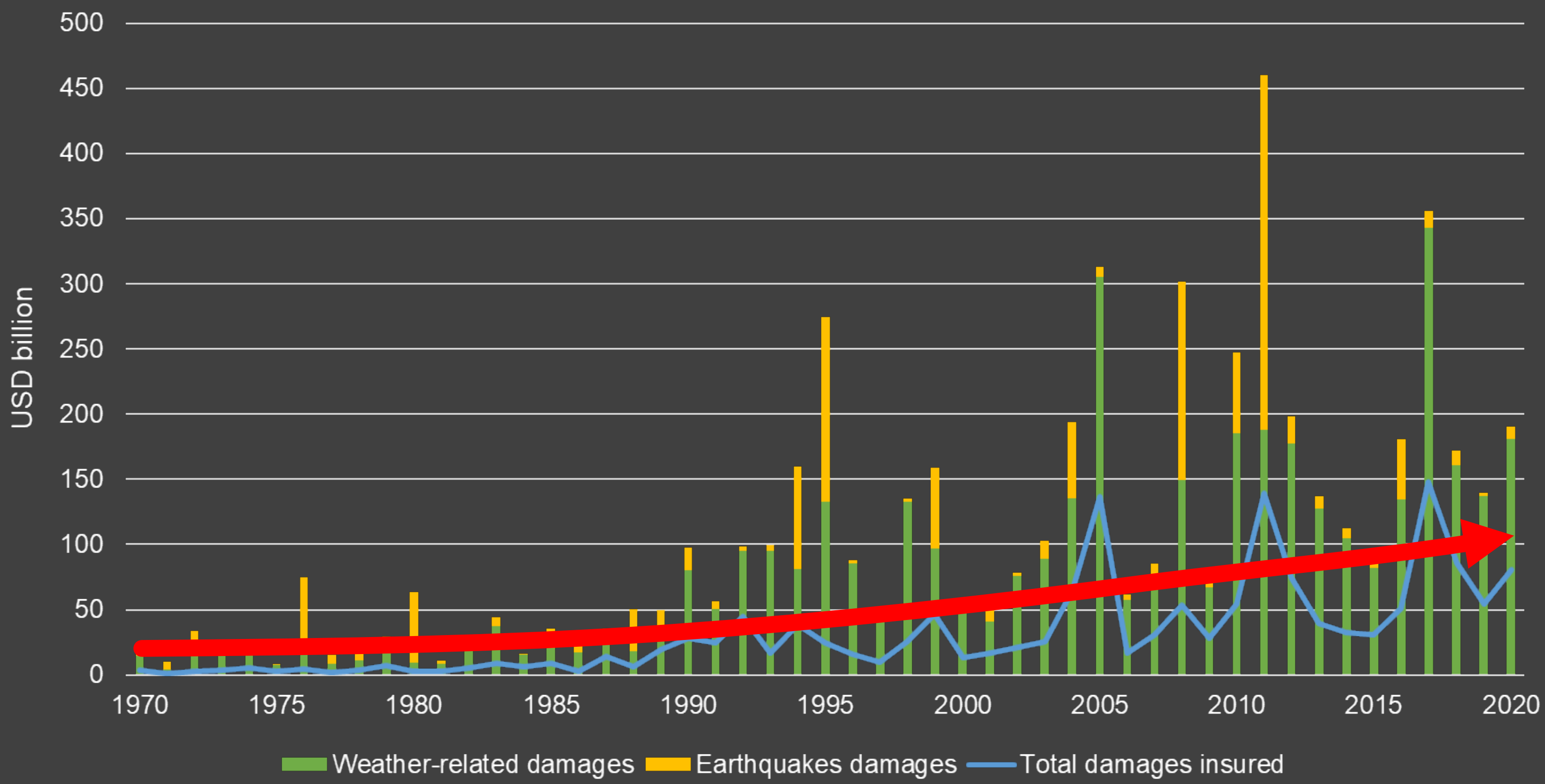
(FRS) FUTURE RESILIENT SYSTEMS

# Risk Assessment – Hazards & Disasters





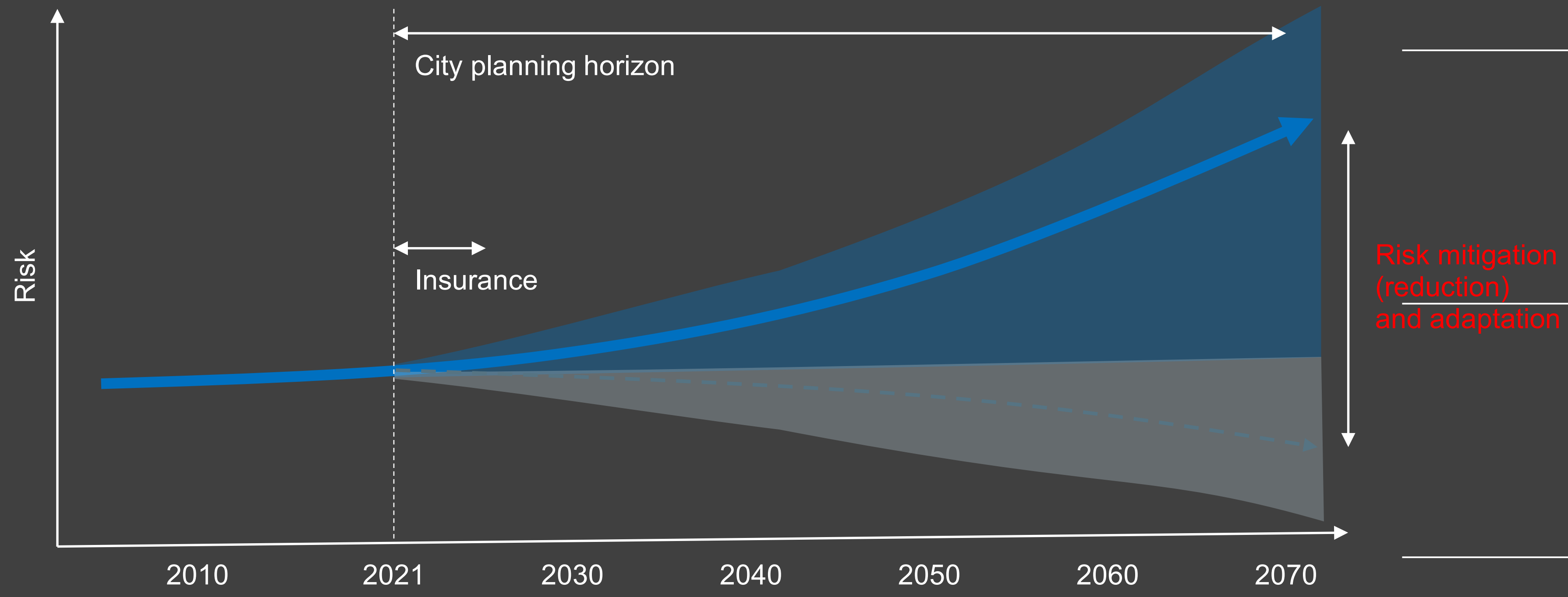
# Increasing Damages from Natural Disasters – Rising Protection Gap




Source of data: Swiss Re, 2021

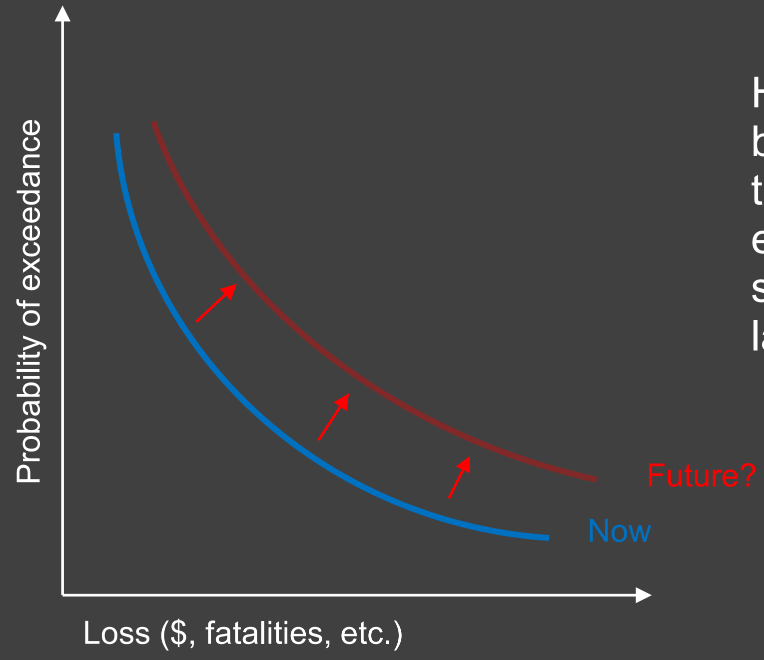
(FRS) FUTURE RESILIENT SYSTEMS

# Risk Horizons




(FRS) FUTURE RESILIENT SYSTEMS

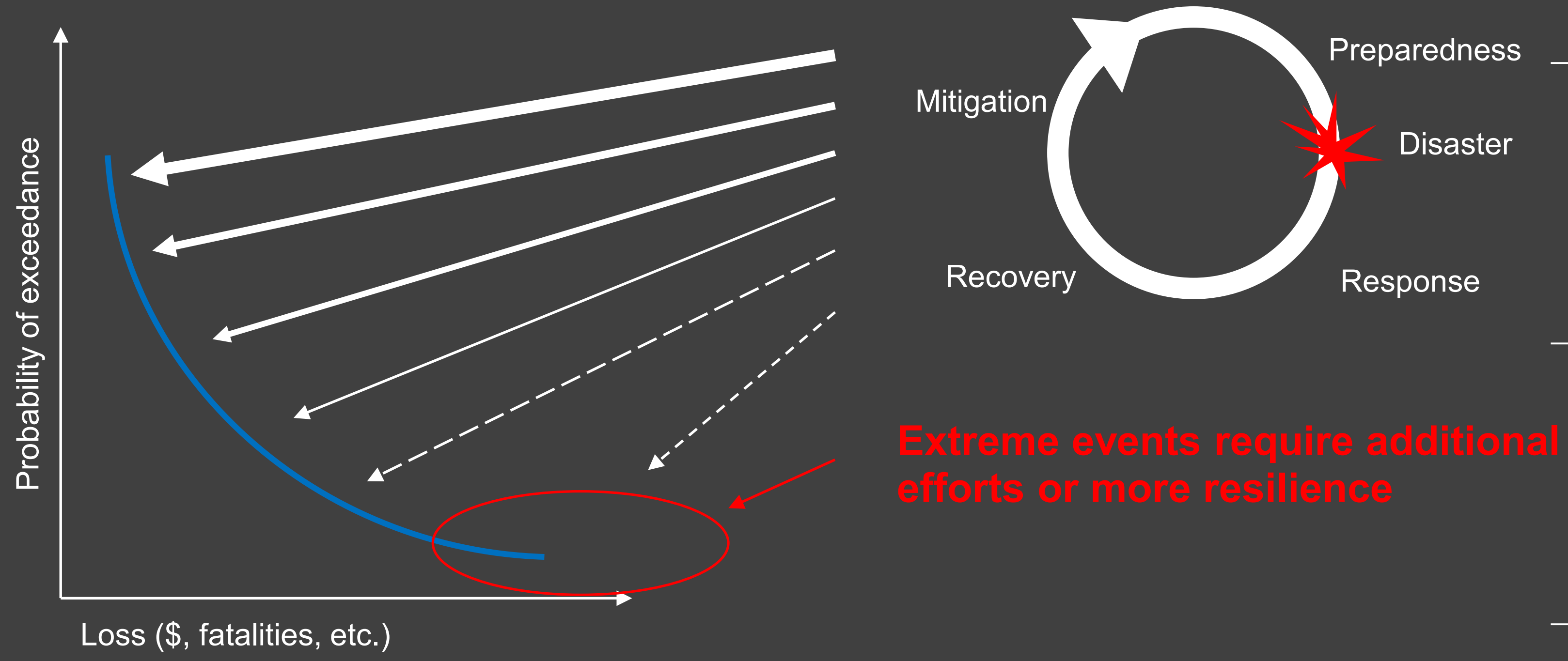
# Risk Assessment – Uncertainty




High **uncertainty** on whether hazards become more severe in the future due to climate change and whether exposure and vulnerability remain stable or increase due to changes in land-use (e.g. urbanisation).

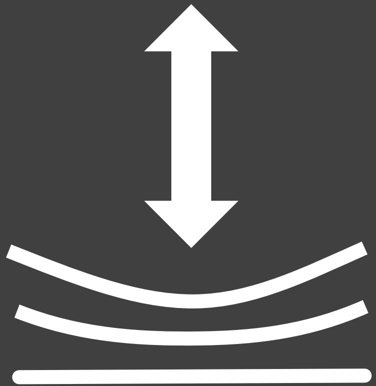
# Disaster Risk Management – Extreme Events

Disaster risk management cycle




(FRS) FUTURE RESILIENT SYSTEMS

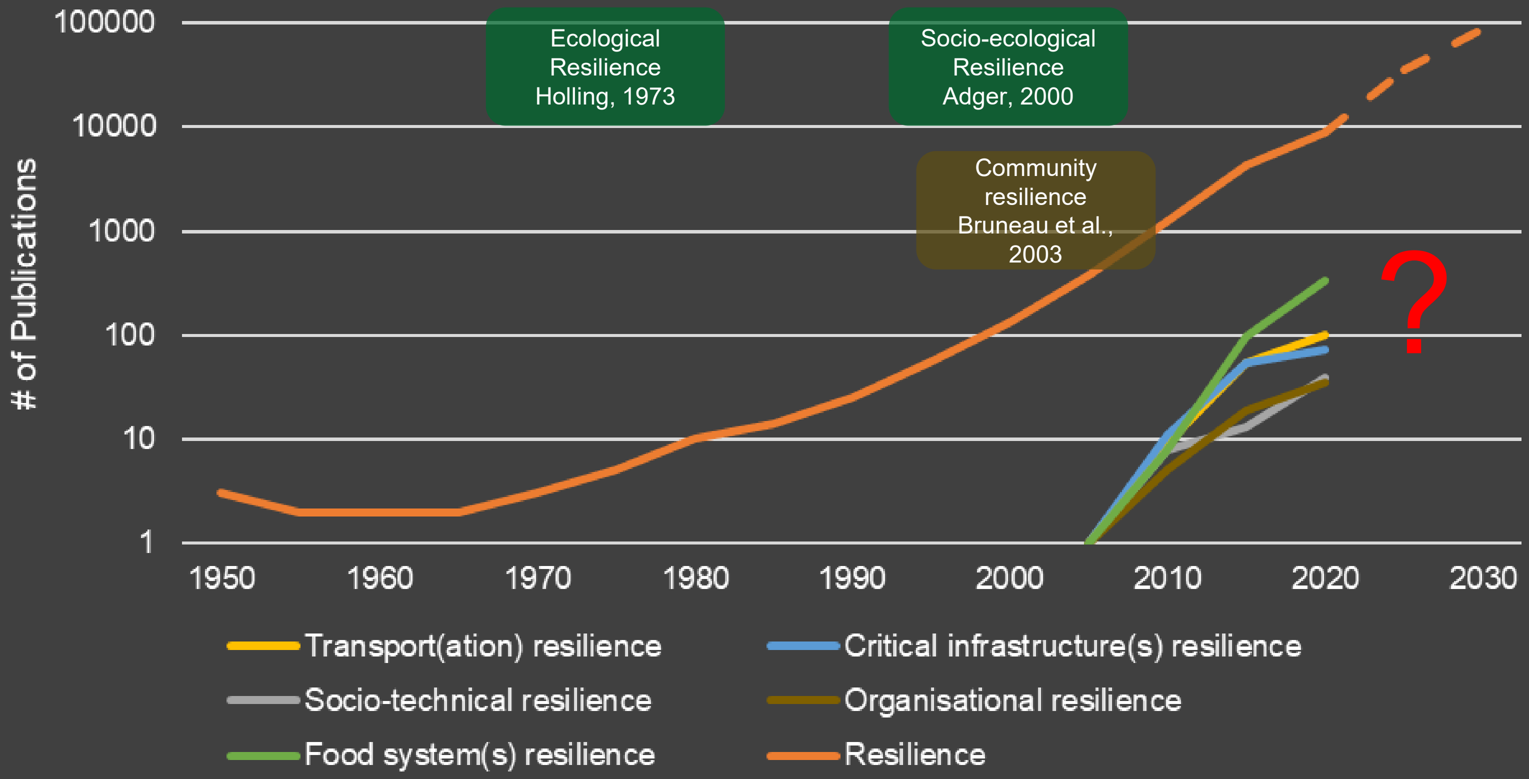
# What is Resilience?



Definition by United Nations Office for Disaster Risk Reduction:

The **ability** of a **system**, **community** or **society exposed to hazards** to **resist**, **absorb**, **accommodate**, **adapt to**, **transform** and **recover** from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions **through risk management**.

# Application of Concept or Resilience in Science

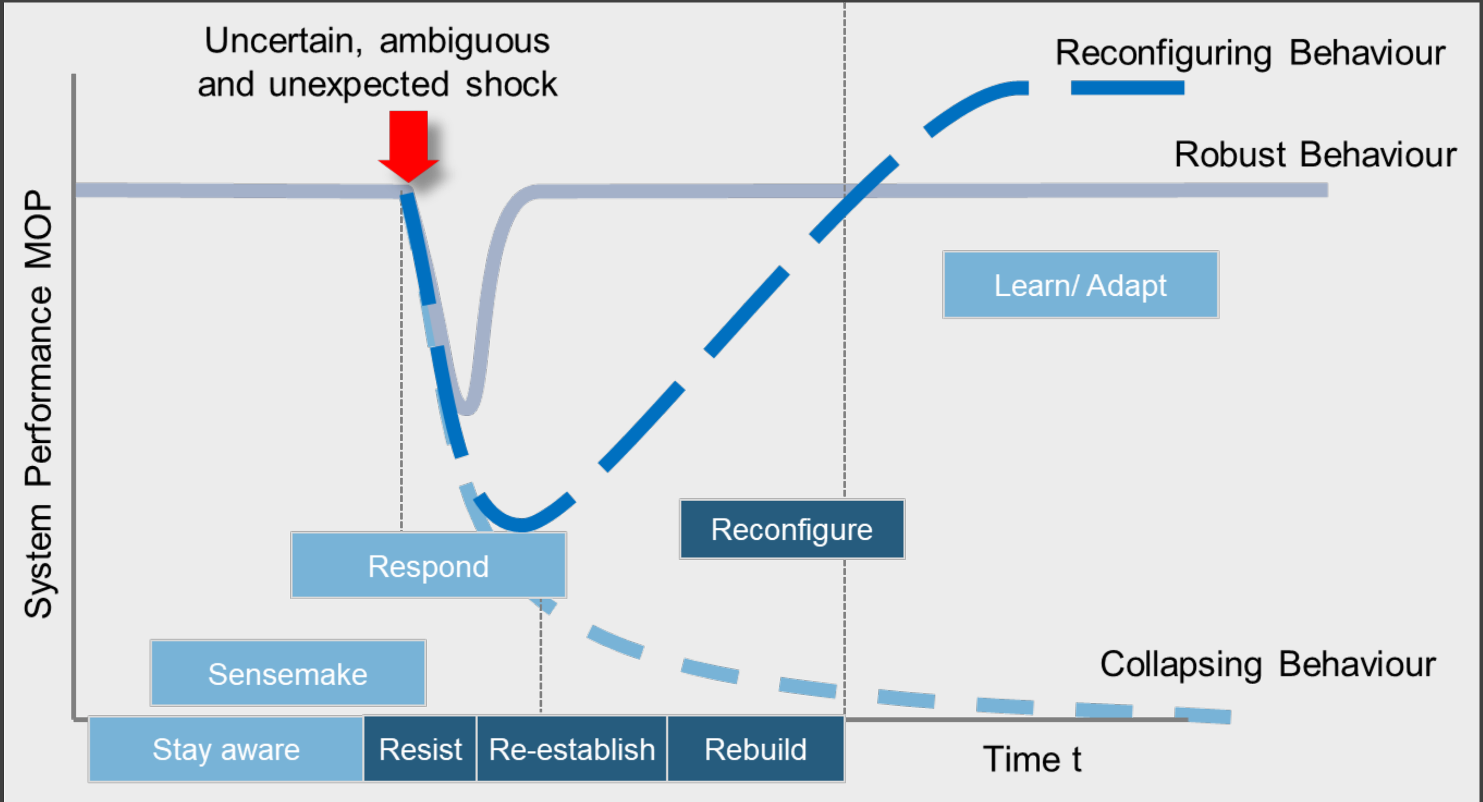



Source of data: Bielefeld Academic Search Engine



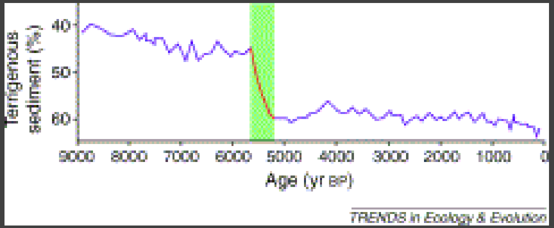
(FRS) FUTURE RESILIENT SYSTEMS

# What is Resilience?



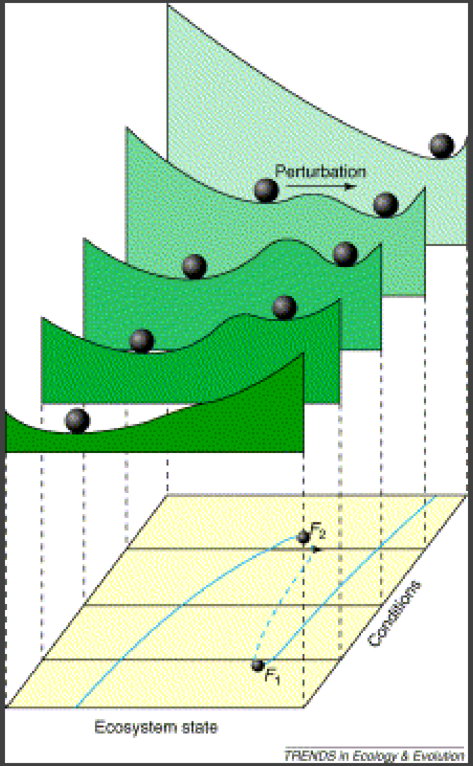

Credit: Hans R. Heinimann, 2019

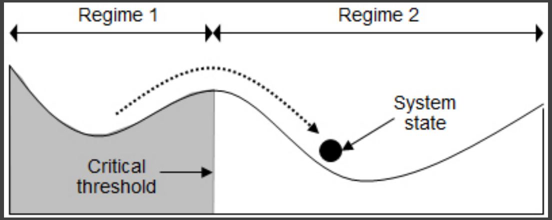
# Regime Shifts




Scheffer and Carpenter, 2003

5,000-6,000 years a ago after a steady decline of terrigenous dust and vegetation cover, an abrupt collapse occurred in the Sahara creating the current desert.




Regime shifts are large, persistent, and usually unexpected changes in ecosystems and social-ecological systems” Biggs et al., 2018, Ecology and Society.

(FRS) FUTURE RESILIENT SYSTEMS

# Regime Shifts – Coral Reefs

Dying coral reefs

*Source: https://www.tropicalsnorkeling.com/live-vs-dead-coral.html#gallery[pageGallery]/3/*

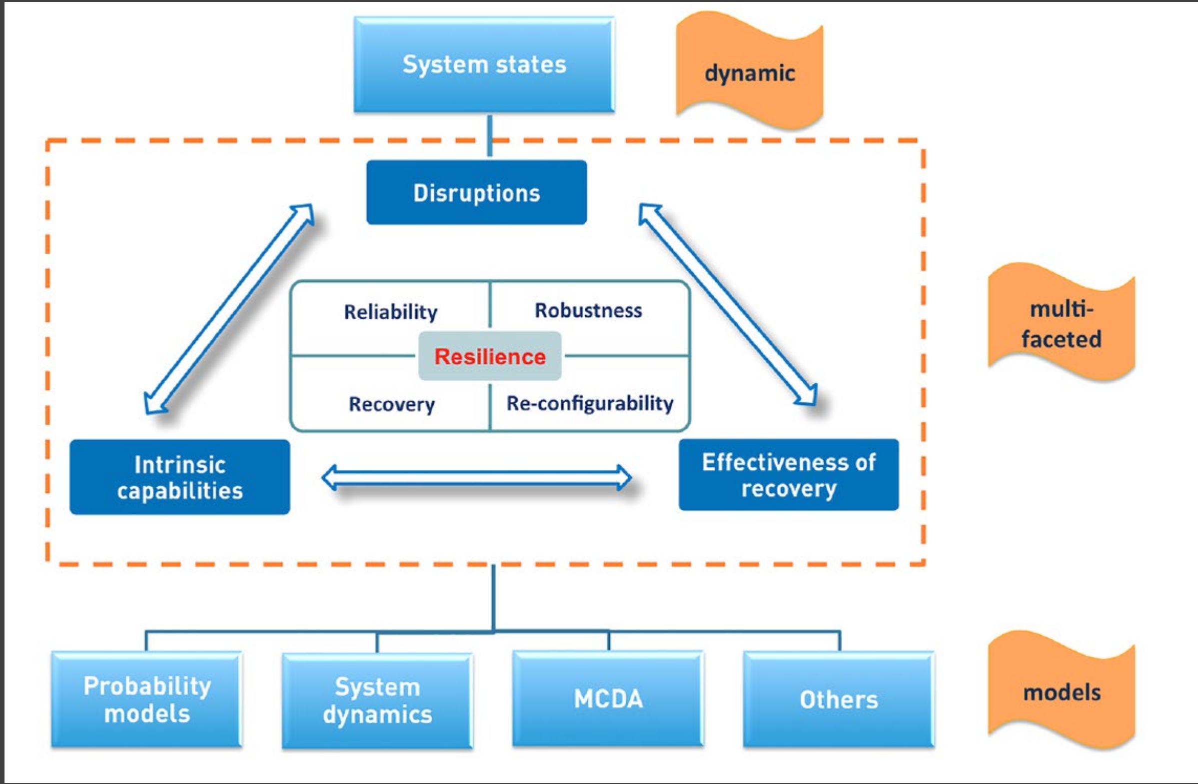
Warming of the ocean due to climate change can lead to death of coral reefs. Dying of coral reefs has severe impacts on marine habitats.

Impacted marine habitats change ocean biodiversity and available resources for humans.



(FRS) FUTURE RESILIENT SYSTEMS

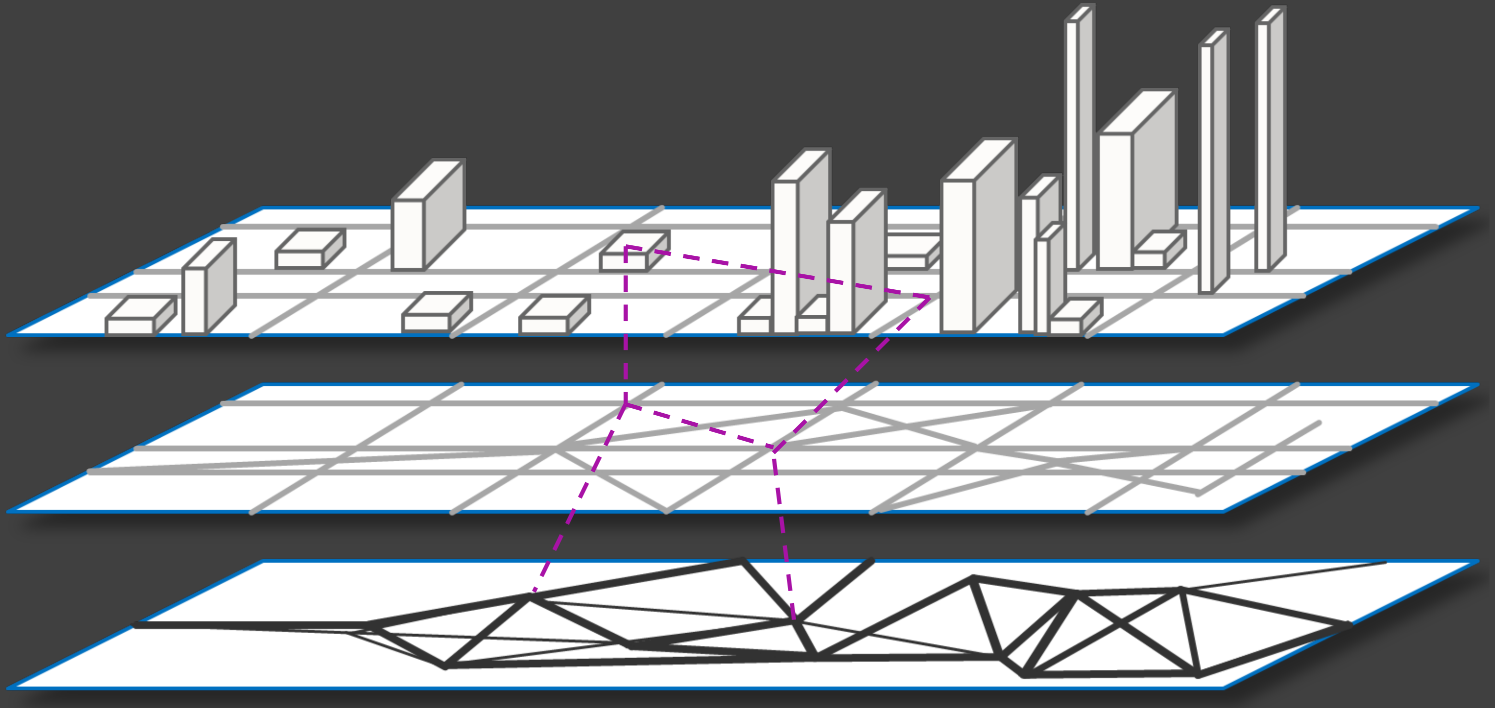
# Conceptualise Resilience for Critical Infrastructure Systems




Increased need to understand intrinsic capabilities of systems and how they interact with users (i.e. people)

Shen, L., Cassottana, B., Heinimann, H.R. & Tang, L.-C. (2020). Large-Scale Systems Resilience: A Survey and Unifying Framework. Quality and Reliability Engineering International, 1-16.

# Interdependencies in Critical Infrastructure Systems



**Above surface:**

Buildings

Roads

**Above/below surface:**

Power lines

Telecommunication

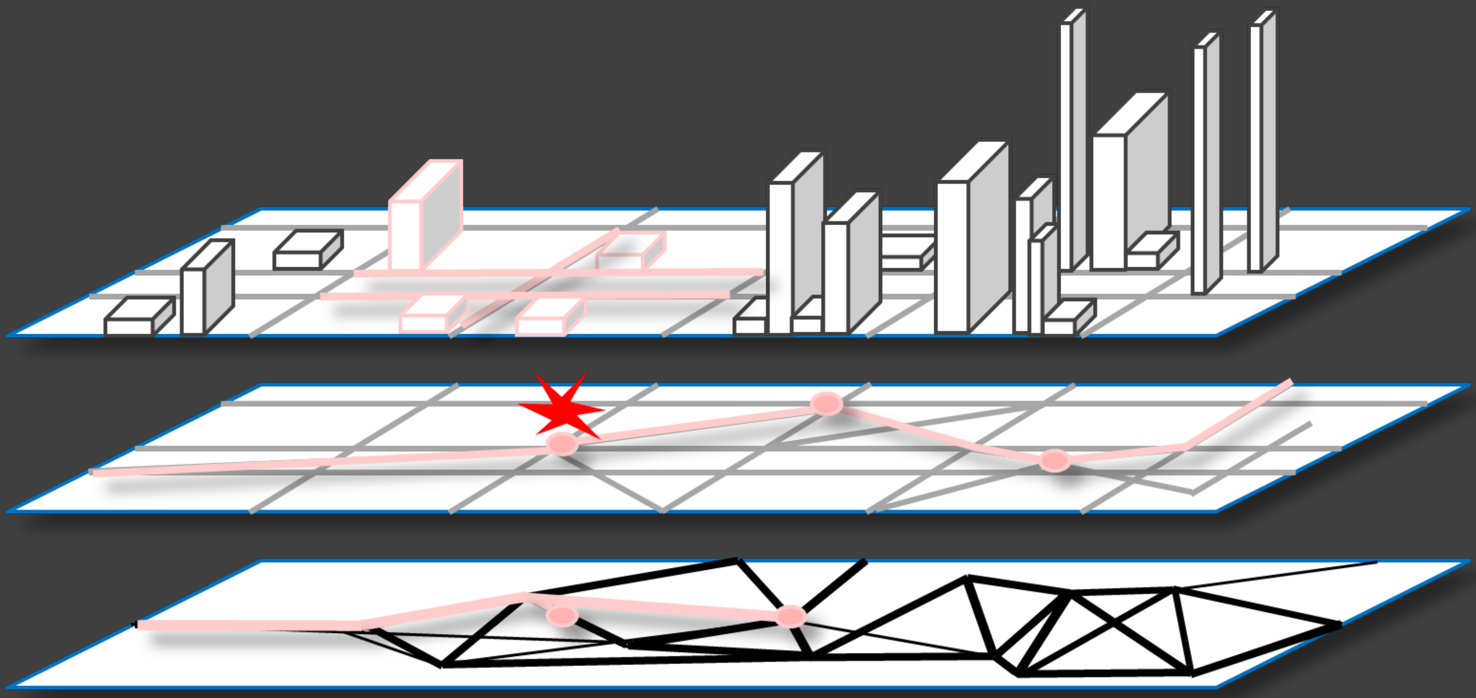
**Below surface:**

Water

Canalisation

→ **Need to understand <u>interdependencies</u>**

# Cascading Effects of a Disruption in Critical Infrastructure Systems



**Above surface:**

Buildings

Roads

**Above/below surface:**

Power lines

Telecommunication

**Below surface:**

Water

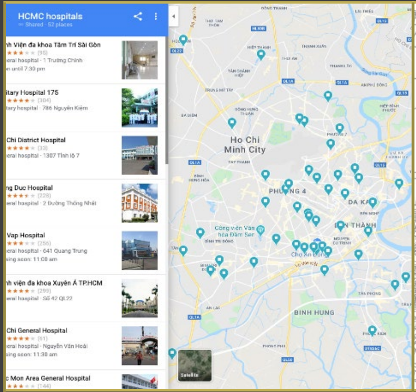
Canalisation

**Goal: to build resilience to manage disruptions**

(FRS) FUTURE RESILIENT SYSTEMS

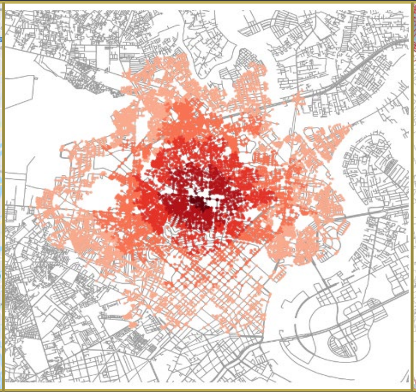
# Workflow to Identify Critical Infrastructure Elements – Road Network

Based on network analysis identify **critical road links** for ensuring critical services, such as medical services and emergency response. Example: Ho Chi Minh City, Vietnam




**Critical service facilities**

**Google Maps**

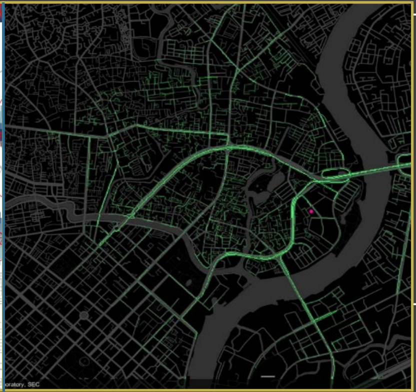


**Service areas identification**

**OSM dataset**

**Disruption analysis**

**FATHOM2 dataset**



**Identification of Critical Infrastructure**

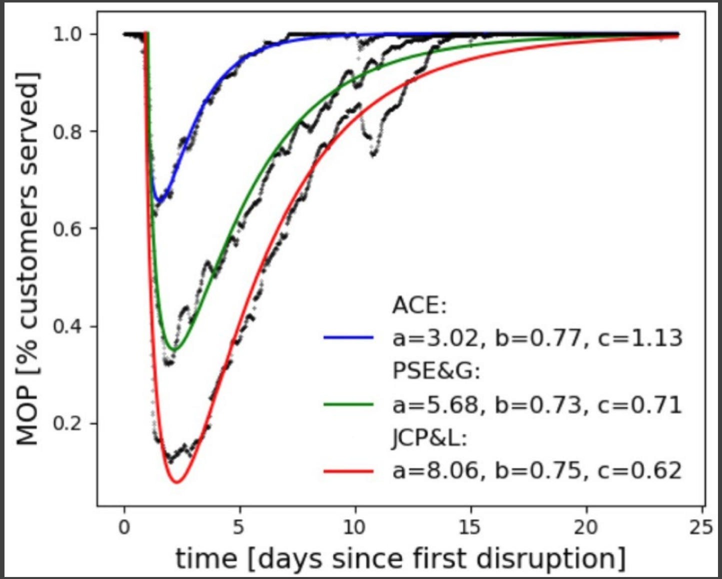
**ur-scape**

Video from UR2020 presentation available: https://www.ur2020.org/agenda/session/440043

# Critical Infrastructure Systems – Recovery of Power Supply

Hurricane Sandy, 2012

## Modelling of recovery process




### Method:

- Fitting of functions from the gamma family to estimate parameters of recovery of power supply for power utilities.

### Findings:

- Absorptive (a), adaptive and restorative (b) capabilities are intrinsic to a system. Recovery time (c) may depend on actions taken.

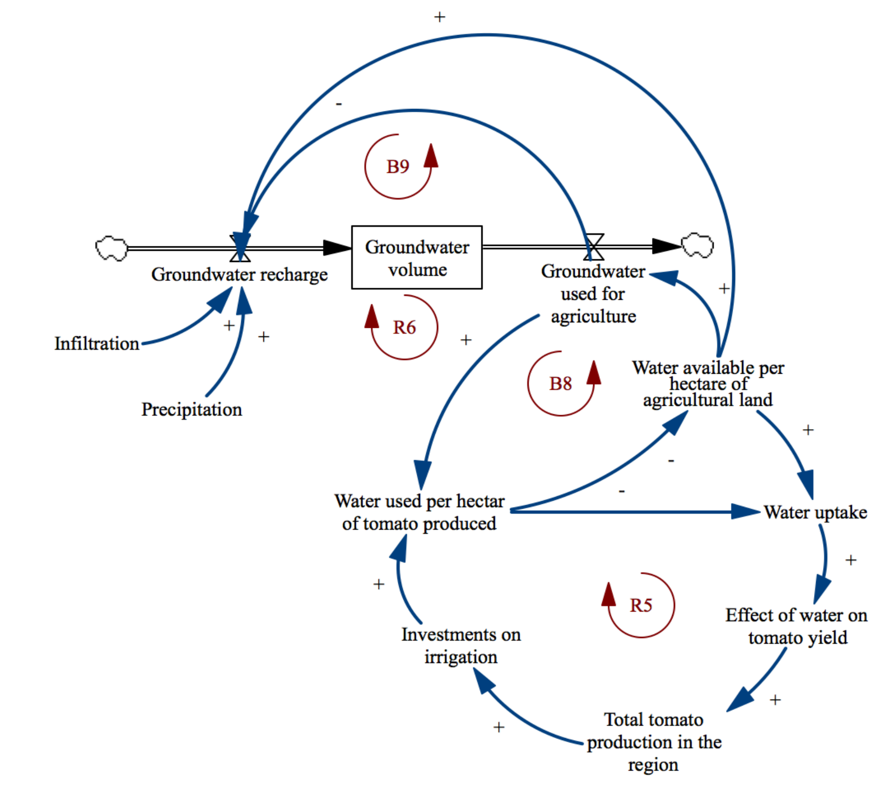
Cassottana, B., Shen, L. & Tang, L.-C. (2019). Modeling the recovery process: A key dimension of resilience. Reliability Engineering and System Safety, 190.

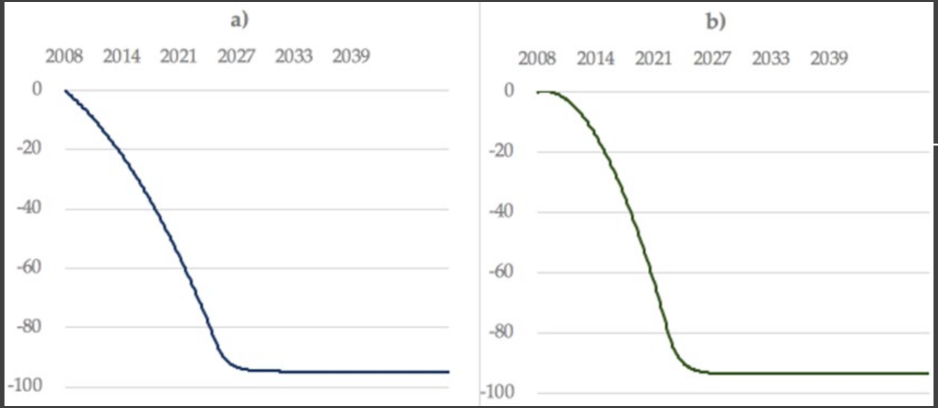


(FRS) FUTURE RESILIENT SYSTEMS

# Food System Resilience – Tomatoes in Morocco

## System Dynamics Model




*Temara groundwater for a) (in Rabat Salé Kénitra Region) and Chtouka groundwater for b) (in Souss Massa Region) dynamics. Relatif water volume compared to the initial time in 2008*

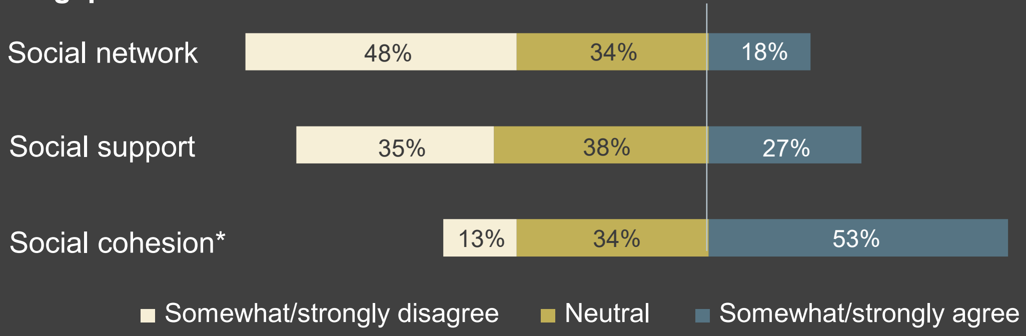
## Findings:

- System dynamics allows to model the various process of a system and determine critical thresholds (e.g. depletion of groundwater)

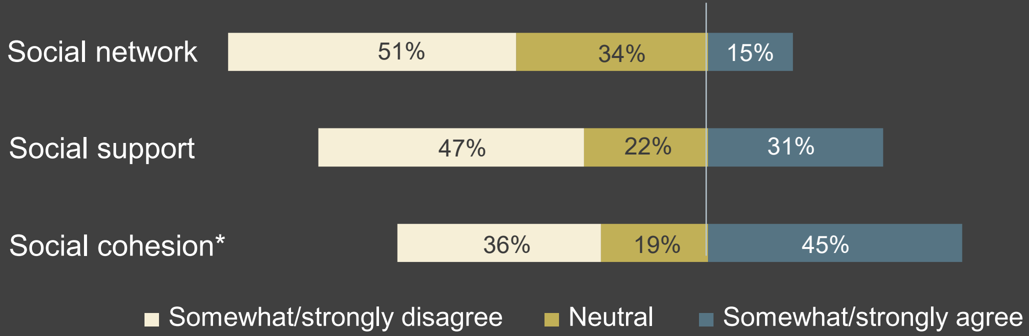
Benabderrazik, K., Kopainsky, B., Tazi, L., Joerin, J. & Six, J. Agricultural intensification can no longer ignore water conservation - A Systemic modelling approach to the case of tomato producers in Morocco. Agricultural Water Management. Accepted.

# Social Resilience: Changes in Social Capital during COVID-19

**Singapore:**




**Switzerland:**




## Method:

- Representative surveys (n=1500) conducted in mid-2020 in Singapore and Switzerland

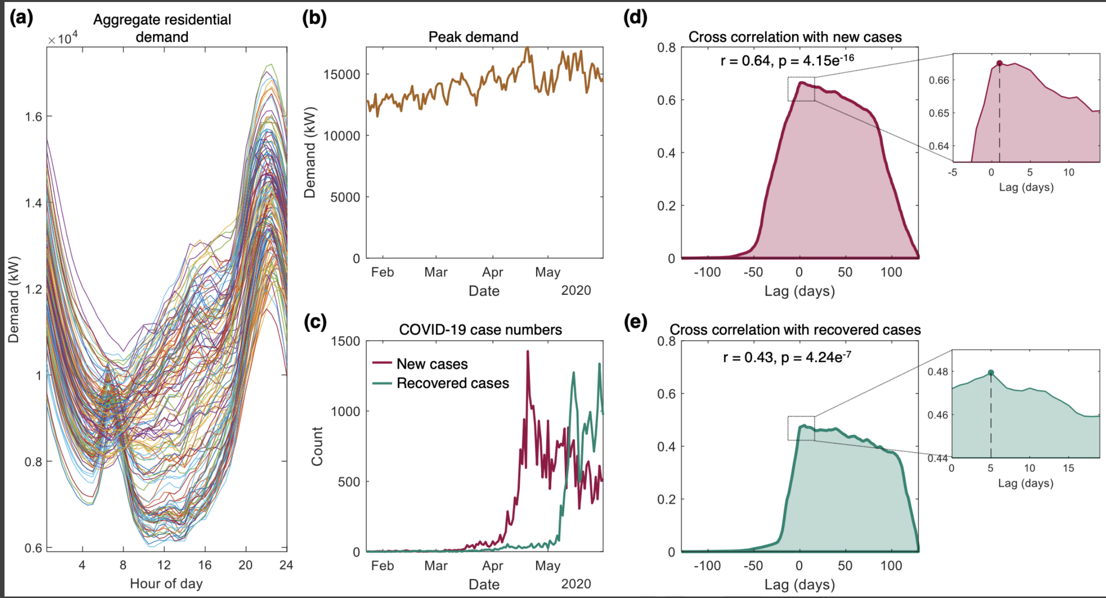
## Findings:

- Rather than collective action, people have to rely on their own abilities to cope with the pandemic. Collective action is less important.
- Need to monitor changes of social capital over time --> second survey.
- Need to analyse how social networks change due to increasing online and virtual interactions.

Schubert, R, Wu, T., Busic, A., Borzino, N. and Joerin, J. (2021). Social Resilience during the COVID-19 Pandemic: Comparisons between Singapore and Switzerland. Technical Note Series, No.1, Future Resilient Systems, Singapore.

# Behaviour-oriented Corruption in Power Systems during COVID-19

## Impact of COVID-19 progression on the Singaporean residential electricity consumption




Method:

- Time-series analysis of residential electricity consumption among 10,246 households in Singapore from 23 January – 31 May 2020.

Findings:

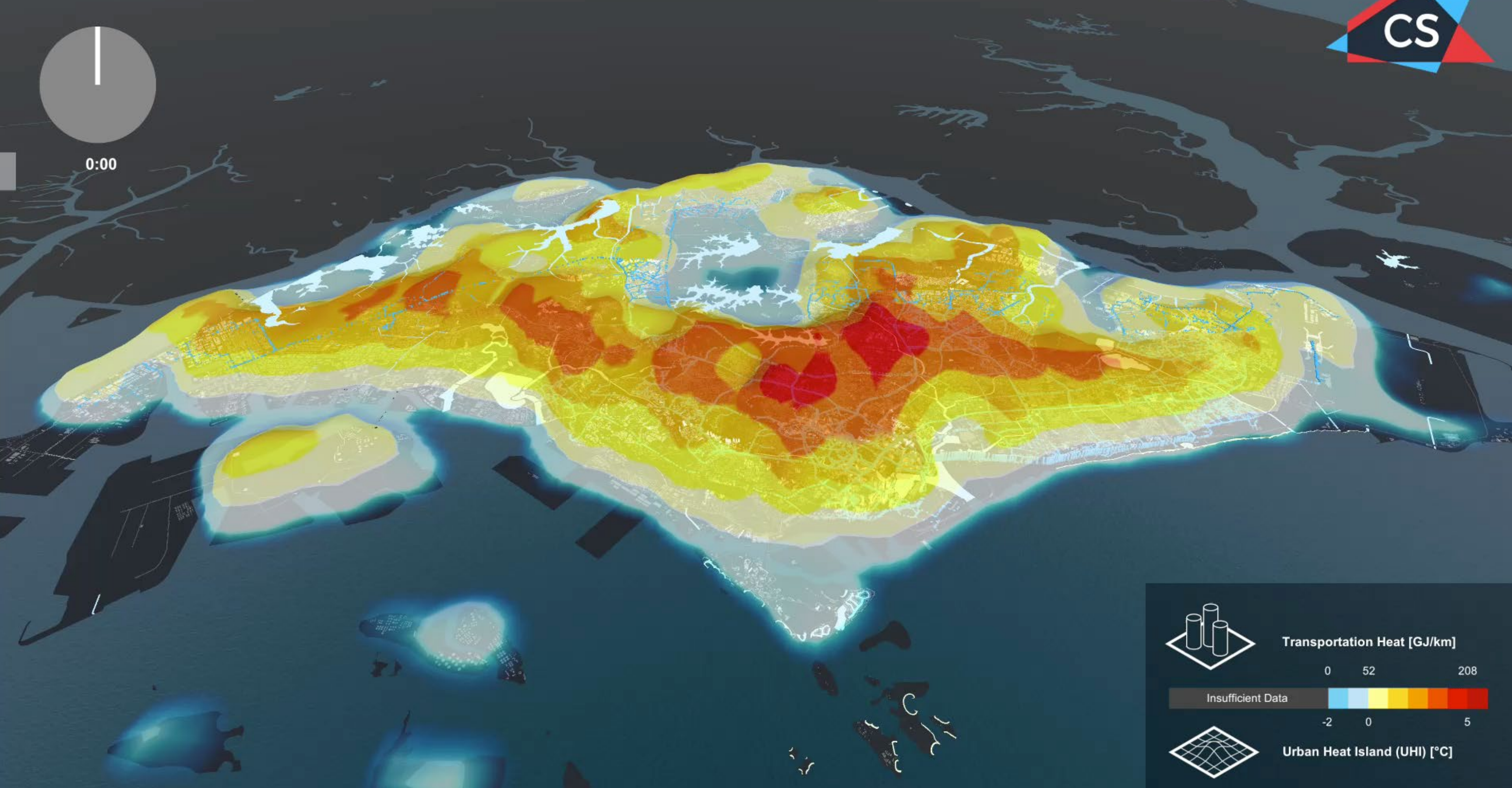
- Peak aggregate household demand are strongly correlated with daily new and recovered COVID-19 case numbers, there is **causality**.
- **Proactive response of Singaporeans to the pandemic even before Circuit Breaker** was enforced.

Raman, G. & Peng, J. C.-H. Electricity consumption of Singaporean households reveals proactive community response to COVID-19 progression. PNAS. Accepted.

(FRS) FUTURE RESILIENT SYSTEMS

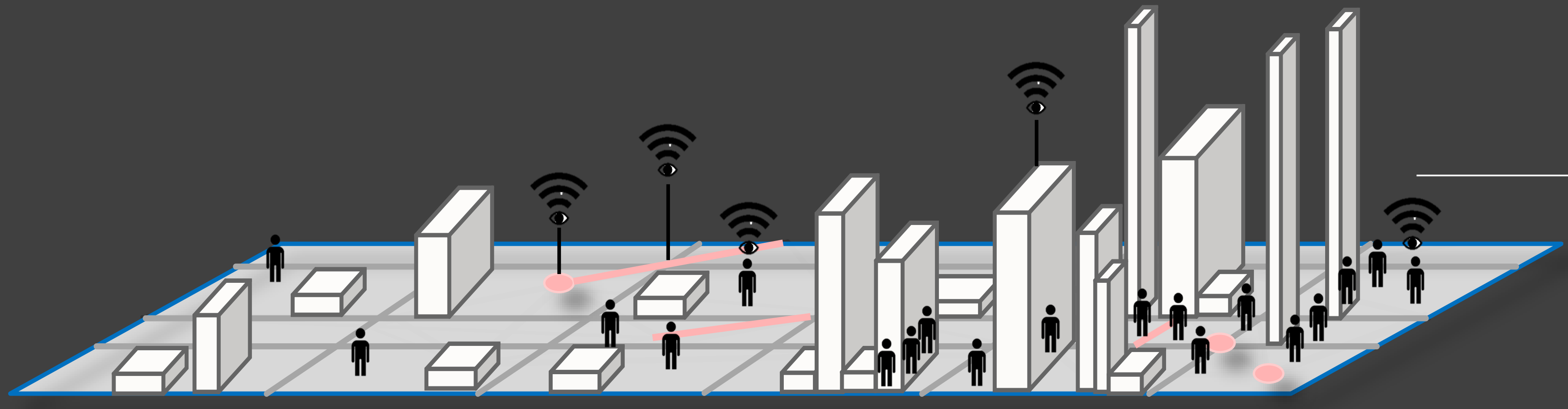
## Singapore Views

### Cooling Singapore



# Develop Smart Cities & Resilient Systems

- Take a system-of-systems approach by linking physical with cyber systems
- Optimise the use and availability of resources in densely populated areas
- Analyse sensor data from networks and people to identify cognitive patterns

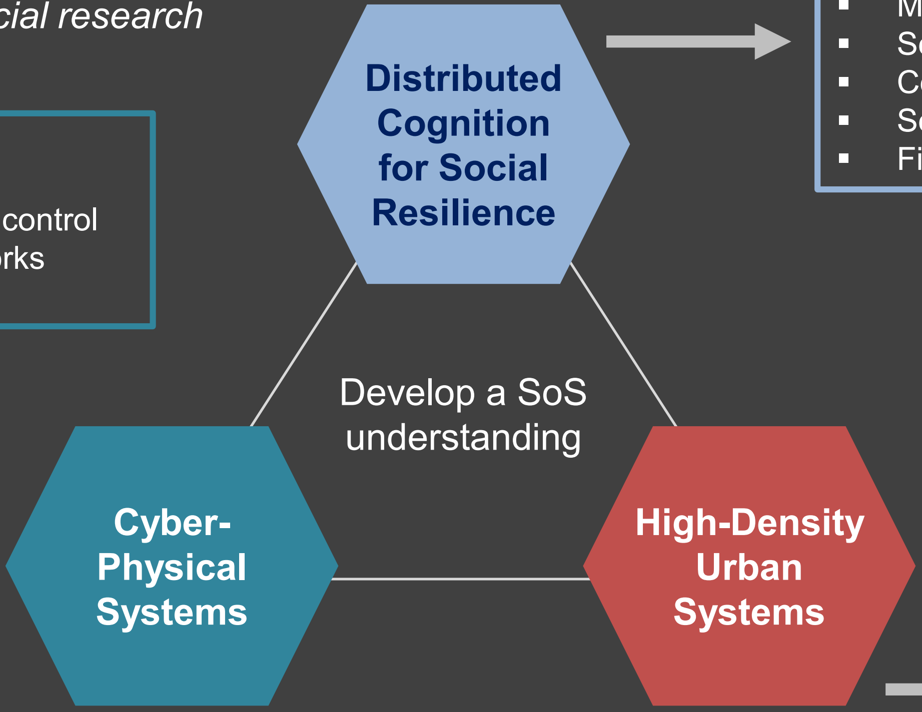


# Summary


- Extreme events are likely to become more frequent due to human-induced climate change.
- Urbanisation leads to a coupling of hazard exposure and vulnerability.
- Insurance may support risk management efforts, but are not sufficient. Planning needs to take into account changing risk exposure and possibility of complex crises.
- Risk management needs to be complemented with resilience management to better deal with unexpected, rare and high-impact events.
- Focus in resilience research is on understanding intrinsic capabilities of systems and how potential disturbances cascade.
- Digitalisation allows individuals to be directly connected to physical systems. Enormous research opportunities to better understand resilience of socio-technical systems.

# FRS II (2020-2025): Programme Structure

*Delivering novel solutions for resilience management through engineering, design and social research*




**Perspectives:**
- Design
- Distributed control
- Data networks
- Digital twin

**Perspectives:**
- Mobile sensor platform
- Soft sensors (social media)
- Context-specific fusion of data
- Social resilience
- FinTech Behaviour

**Perspectives, link HDUS to:**
- Urban metabolism
- Optimal pathways for the future
- Climate change
- Financial systems

Dr Jonas Joerin
jonas.joerin@sec.ethz.ch

28 July 2021

frs.ethz.ch

CREATE ETH zürich

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE NUS STEVENS ILLINOIS

(FRS) FUTURE RESILIENT SYSTEMS

# Critical Infrastructure Systems Resilience

*2021 APRU Multi-Hazards Summer Lecture Series: Creating a Resilient Society against Multiple Hazards*

29 July 2021

Dr Yi Wang

Postdoctoral researcher
Future Resilient Systems, Singapore ETH Centre

CREATE ETH zürich NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE NUS STEVENS ILLINOIS

(FRS) FUTURE RESILIENT SYSTEMS

# Outline

- **An introduction into critical infrastructure systems resilience**
  - What are critical infrastructures
  - Complex interdependencies
  - Defining critical Infrastructure resilience and its dimensions
- **Transportation systems resilience**
  - Global disaster risks exposure
  - How to achieve infrastructure resilience: Ho Chi Minh City case study
    - BRT Corridor project planning with ur-scape
    - Lifeline preparedness for flood risks
- **Summary**

# Critical infrastructure

**Assets, systems, and networks** that provide **essential services** for the security of a nation, its economic prosperity, and the health and safety of its citizens.

# Critical infrastructure services


**Direct damages** from disasters to the power generation and transport infrastructure are estimated at **US$18 billion** a year in low- and middle income countries globally.

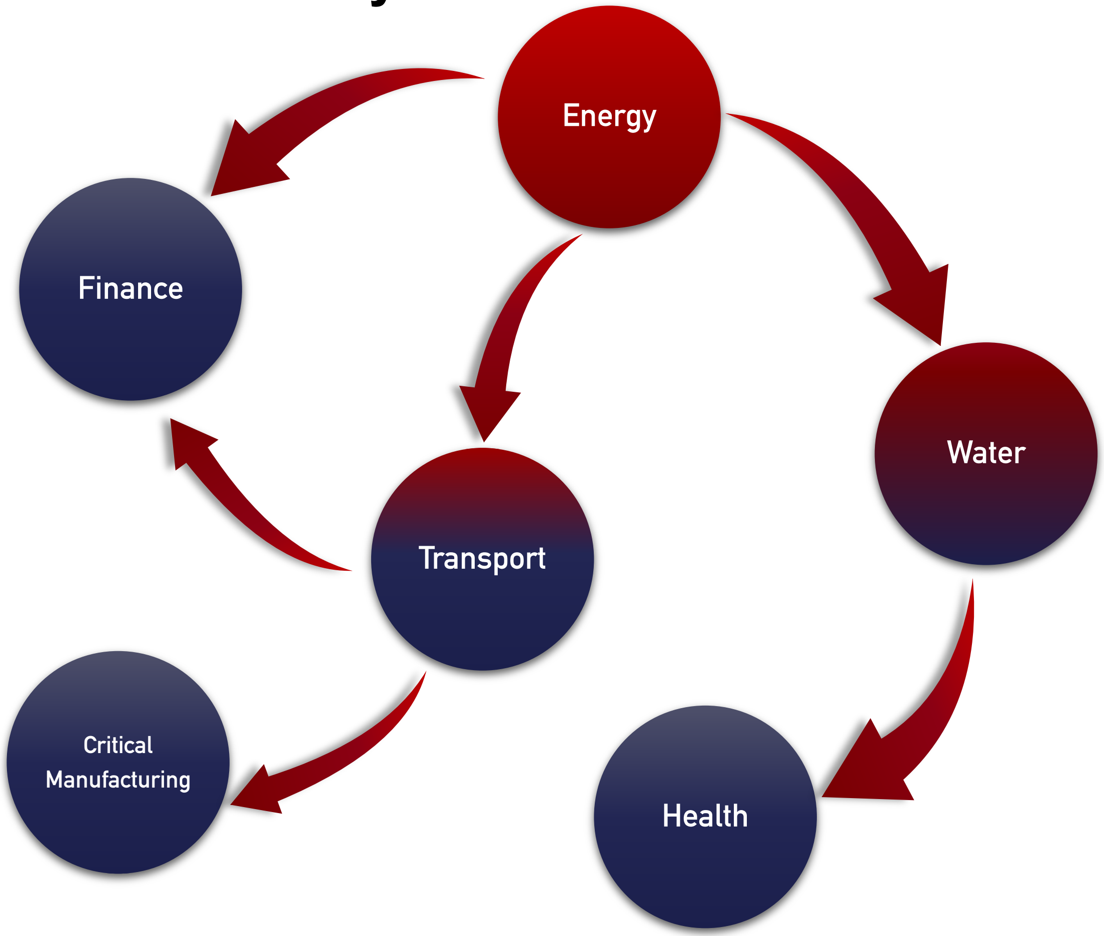
But the estimated cost of the **associated disruption to services** (energy and transport) ranges **from US$391 billion to US$647 billion**, at least 20 times larger.

# In February 2021, as a result of deadly winter storm and record low temperatures in Texas, USA, 4.5 million people were cut off from power.

A utility structure is encased in ice on Feb. 15, 2021 in Houston.
Source: https://www.texastribune.org/2021/02/16/texas-power-outage-ercot/

# Interdependence of Critical Infrastructure Systems

- A massive **electricity** generation failure, more than 4.5 million homes and businesses were left without power.
- **Water** service was disrupted for more than 12 million people due to pipes freezing and bursting.
- Intermodal **freight** network was shut down and train lengths were reduced for safety reasons.
- Water treatment facility lost power, forcing a city-wide boil water notice to be issued. Non-urgent surgeries were cancelled and patients were transferred due to the water shortage and impacted heating system.
- The power outages have also had a major impact on rail traffic that is critical for many supply chains, leading to impacts to manufacturing, warehousing and store operations.
  - Shut down semiconductor plants clustered around Austin, further disrupting a supply chain that has already been falling short of customer needs.
- Electricity prices on the state's wholesale market soared by $47 billion. Some energy firms made billions in profits, while others went bankrupt.

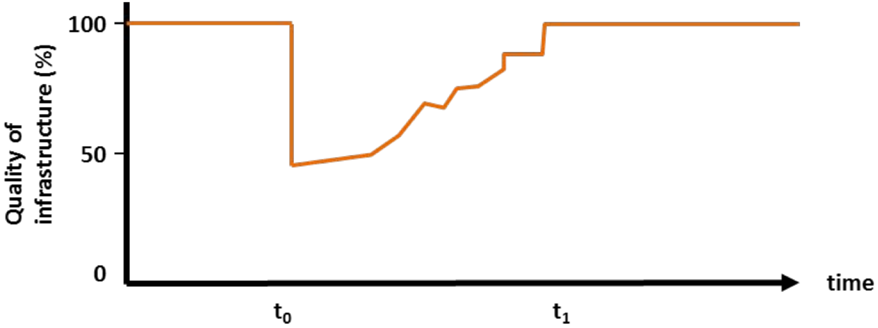


# Critical Infrastructure Resilience

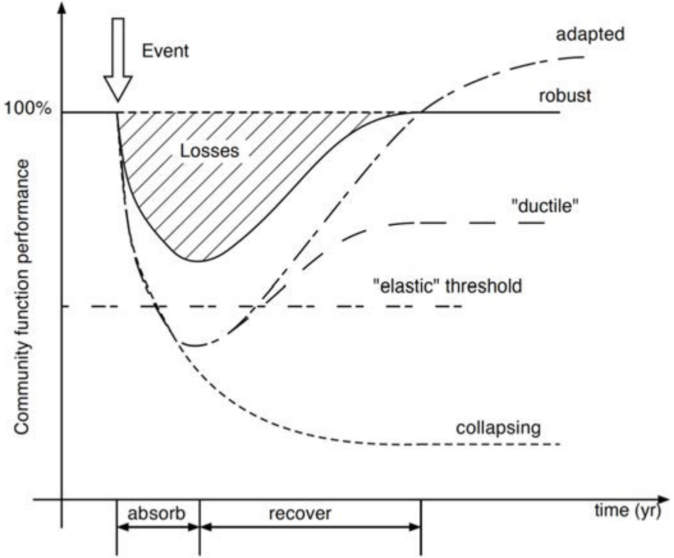
**The resilience "triangle"** (Bruneau et al., 2003) - technical basis for resilience assessment

The ability of the system to

- reduce the chances of shocks
- absorb a shock if it occurs
- recover quickly after a shock




- Recovery behaviours





Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., . . . von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733–752.

# Critical Infrastructure Resilience

## **Towards a comprehensive modelling framework** - high-level dimensions

- “TOSE” by Bruneau et al. (2003)
- US National Infrastructure Advisory Council (2010)
    - People and processes
    - Infrastructure and assets.

**E**conomic

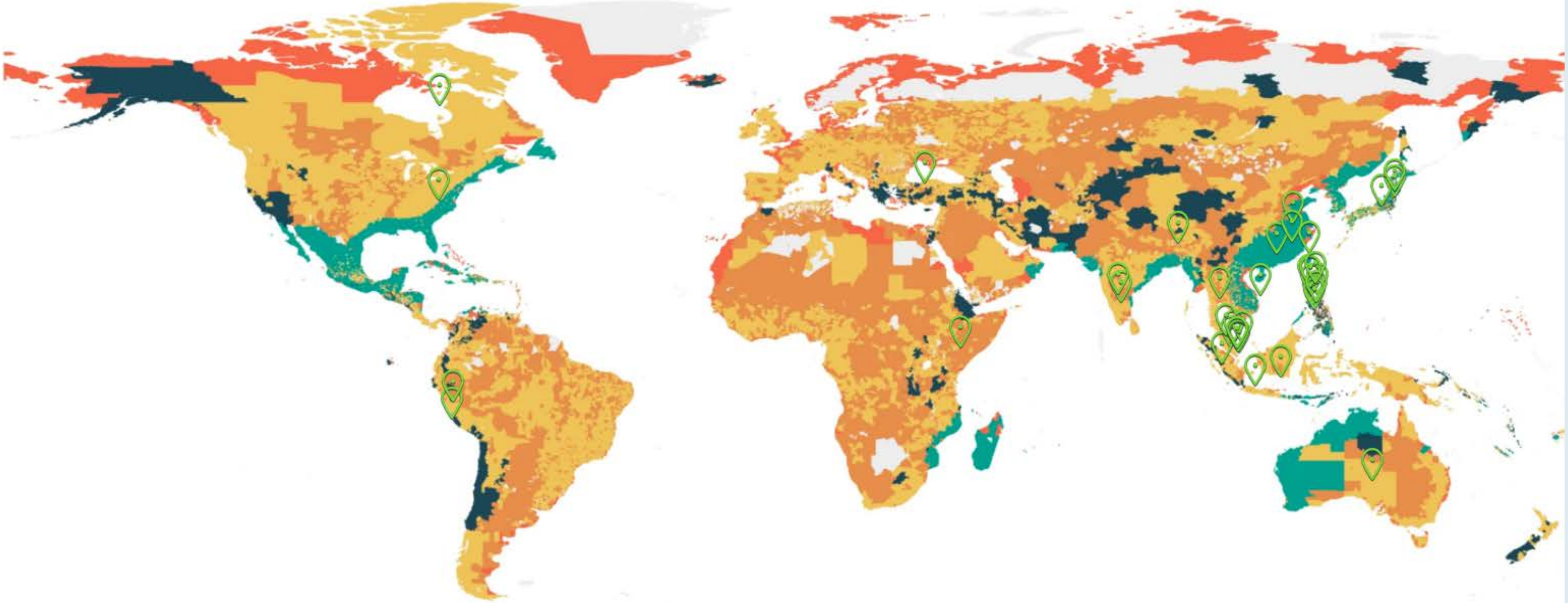
**S**ocial

**T**echnical

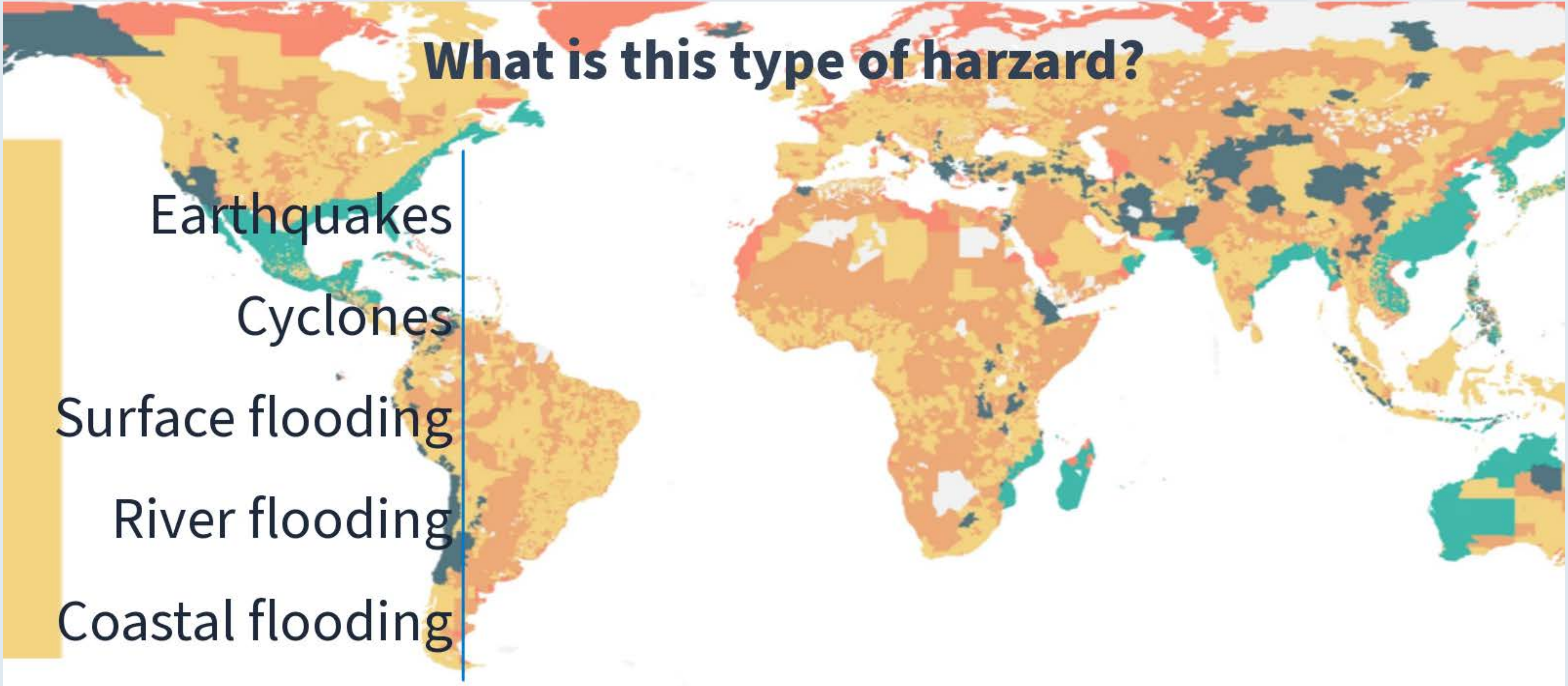
**O**rganisational

National Infrastructure Advisory Council (NIAC) (2010) *A framework for establishing critical infrastructure resilience goals.* Final report and recommendations by the council. Washington DC.

# Please click on the location where you are at



Powered by Poll Everywhere



# What is this type of harzard?

Earthquakes

Cyclones

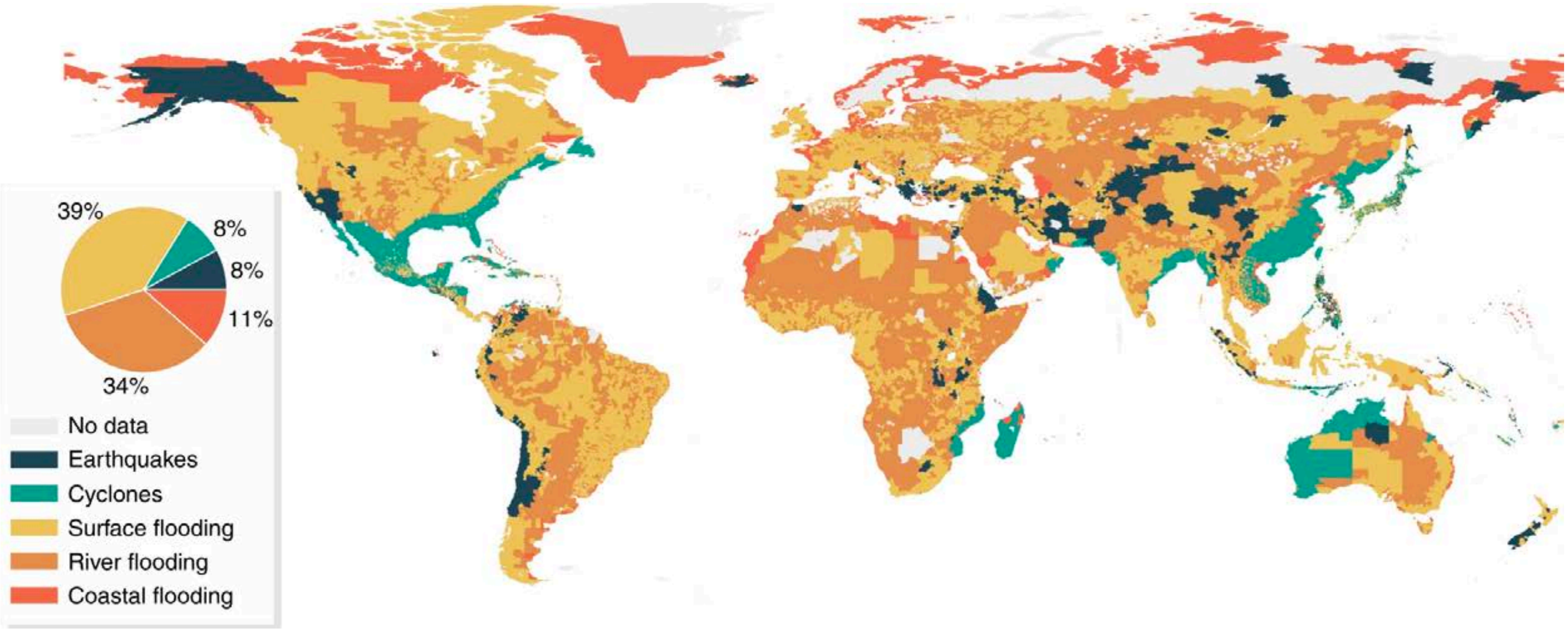
Surface flooding

River flooding

Coastal flooding

# Transportation Infrastructures and disaster risks

Global dominant hazard exposure per region (Koks et al., 2019)

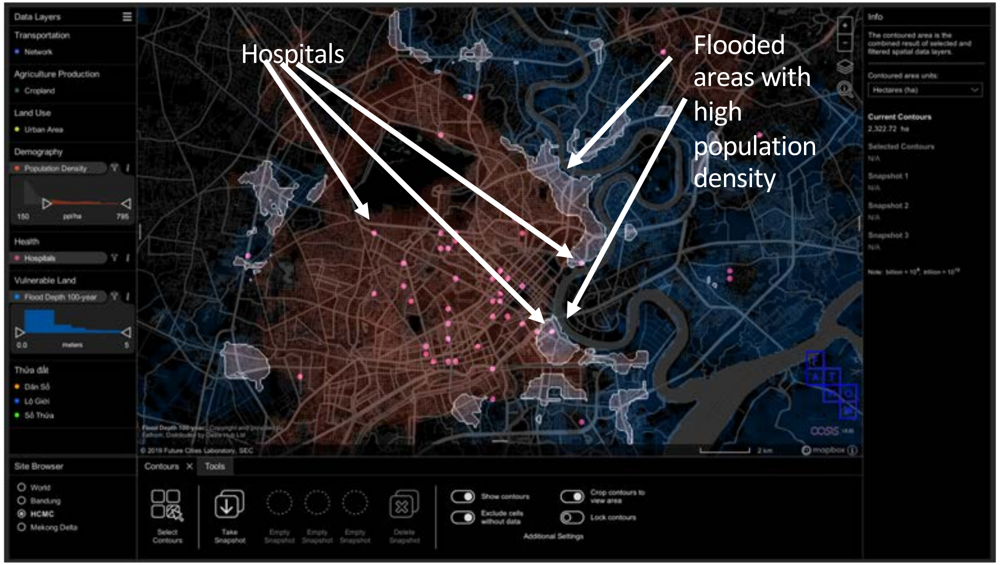



Source: Koks, Elco E., et al. "A global multi-hazard risk analysis of road and railway infrastructure assets." *Nature communications* 10.1 (2019): 1-11.

# Public Critical Infrastructure Planning with Resilience-thinking

A research collaboration with the World Bank Group and Ho Chi Minh City, Vietnam

**Future Resilience Systems:** Dr. Jonas JOERIN, Dr. Yi WANG, Dr. Dr. Peter LUSTENBERGER
**Future Cities Lab Global:** Prof. Stephen CAIRNS, Michael Joos

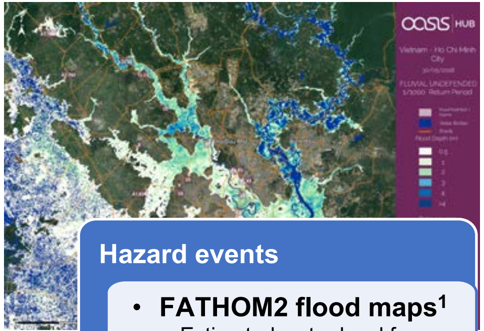



- Identification of "hotspot/bottlenecks" under threat
- Contingency plans (e.g. lifeline protection)
- Structural measures for disaster risk reduction

ur-scape adapted to HCMC for a flooding with 100-year return period

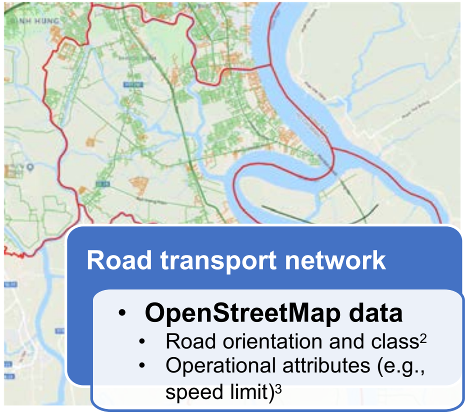
# Digital workflow

[1] FATHOM. "Fathom-Global." from https://www.fathom.global/fathom-global (2019).
[2] Ramm, Frederik, et al. "OpenStreetMap Data in Layered GIS Format." *Version 0.6 7* (2014).
[3] Zilske, Michael, Andreas Neumann, and Kai Nagel. *OpenStreetMap for traffic simulation*. Technische Universität Berlin, 2015.



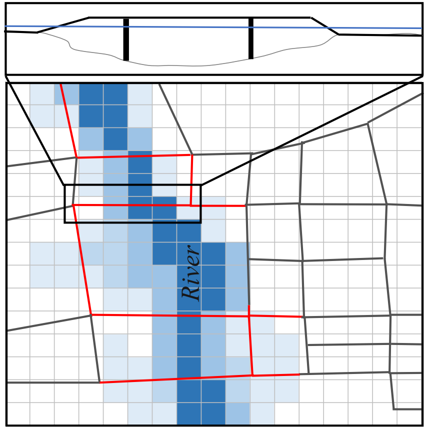

## Hazard events

- **FATHOM2 flood maps[1]**
  - Estimated water level for raster cell (~90m)
  - 10 RP, fluvial and pluvial



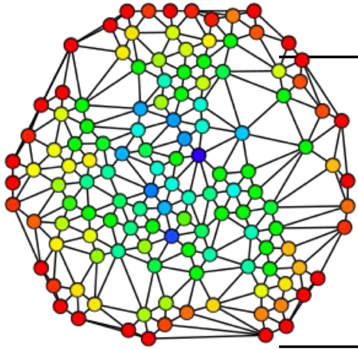
## Road transport network

- **OpenStreetMap data**
  - Road orientation and class[2]
  - Operational attributes (e.g., speed limit)[3]




## Exposure and disruption

- **Functionality loss**
  - Road closure due to “heavy flooding” (inundation depth>0.3 m)
  - Highest cell value (water level)



An undirected graph coloured based on the **betweenness centrality** of each vertex from least (red) to greatest (blue).

## Critical component Analysis

- **Topological analysis**
  - Network science indicators
  - Before/after a disruptive event

# Critical Infrastructures Planning in ur-scape: BRT Corridor

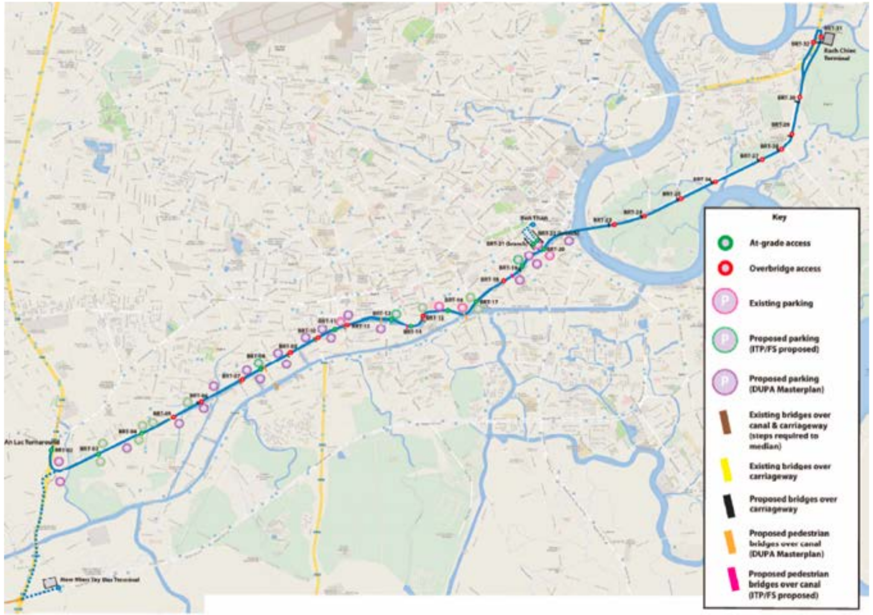



Figure: Ho Chi Minh BRT corridor

Source: Ho Chi Minh BRT Technical Study Final Report September 2014 V1.0, Integrated Transport Planning Ltd

- **Catchment area analysis**
  - Identify beneficiary/impacted communities
  - Assist travel demand planning
- **Component level – “vulnerability”**
  - Flood risks screening for critical infrastructures (e.g., stations and road segments)

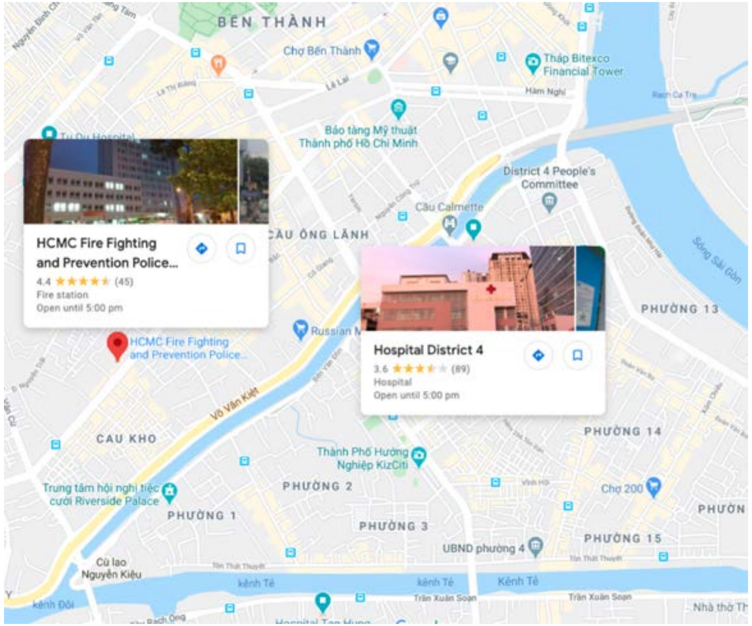
# Critical Infrastructures Planning in ur-scape: BRT Corridor




(FRS) FUTURE RESILIENT SYSTEMS

# Critical Infrastructure Services

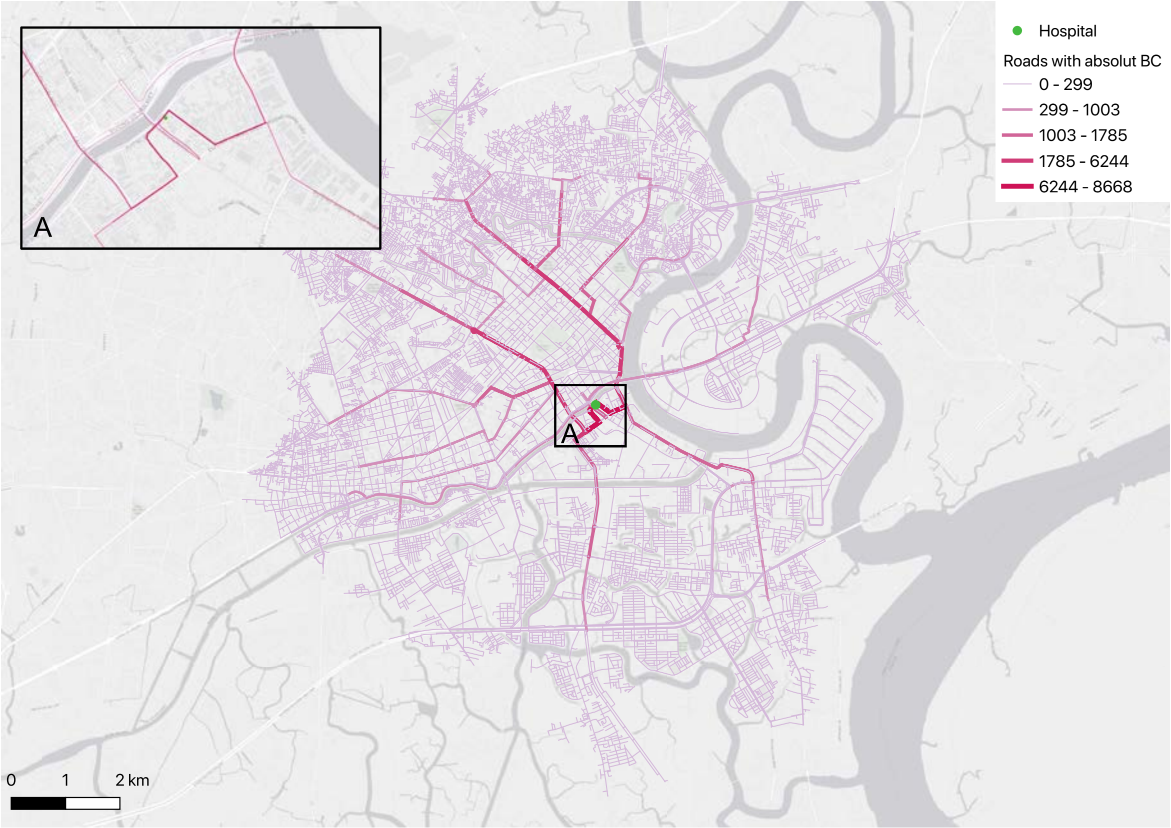
## Road Transportation Network for Supporting Emergency Services




- **Network level - “criticality”**
  - Identification of “hotspots” based on network science: the lifeline under normal and flooded situations
  - Wider social costs consideration by incorporating human assets

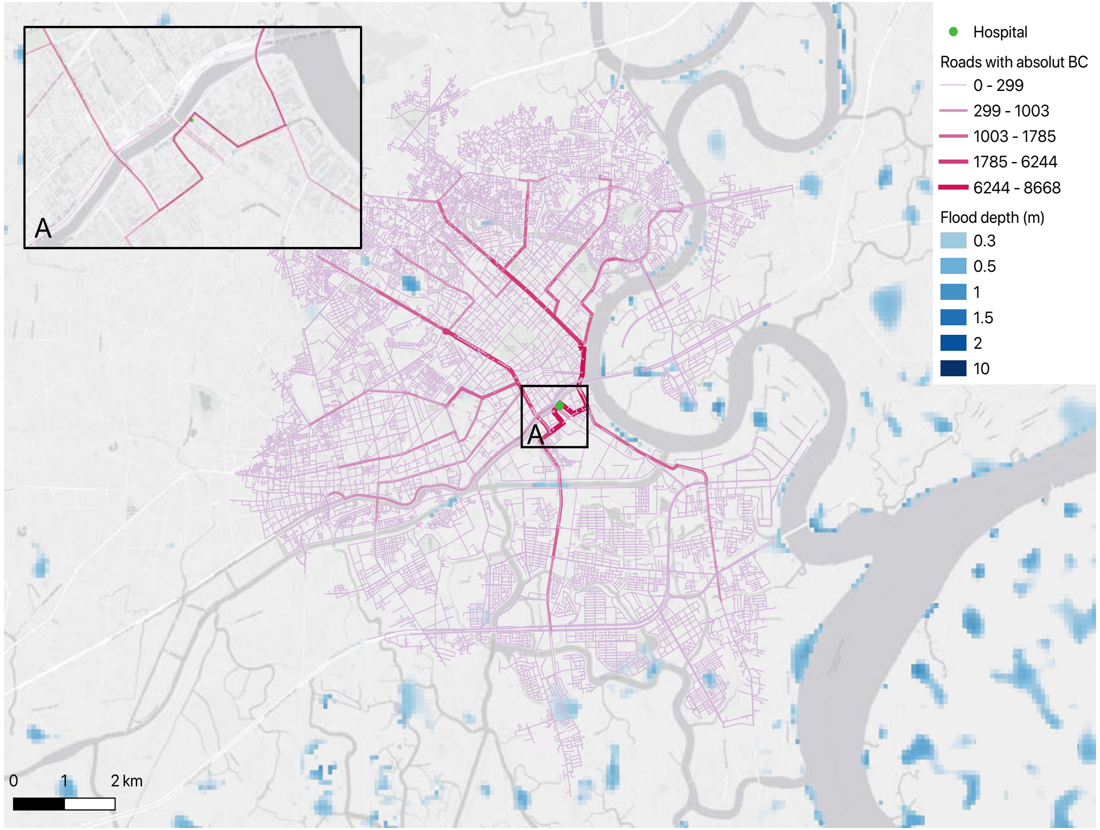
# Road criticality in the 10-min catchment network of District 4 Hospital

(No disruption)

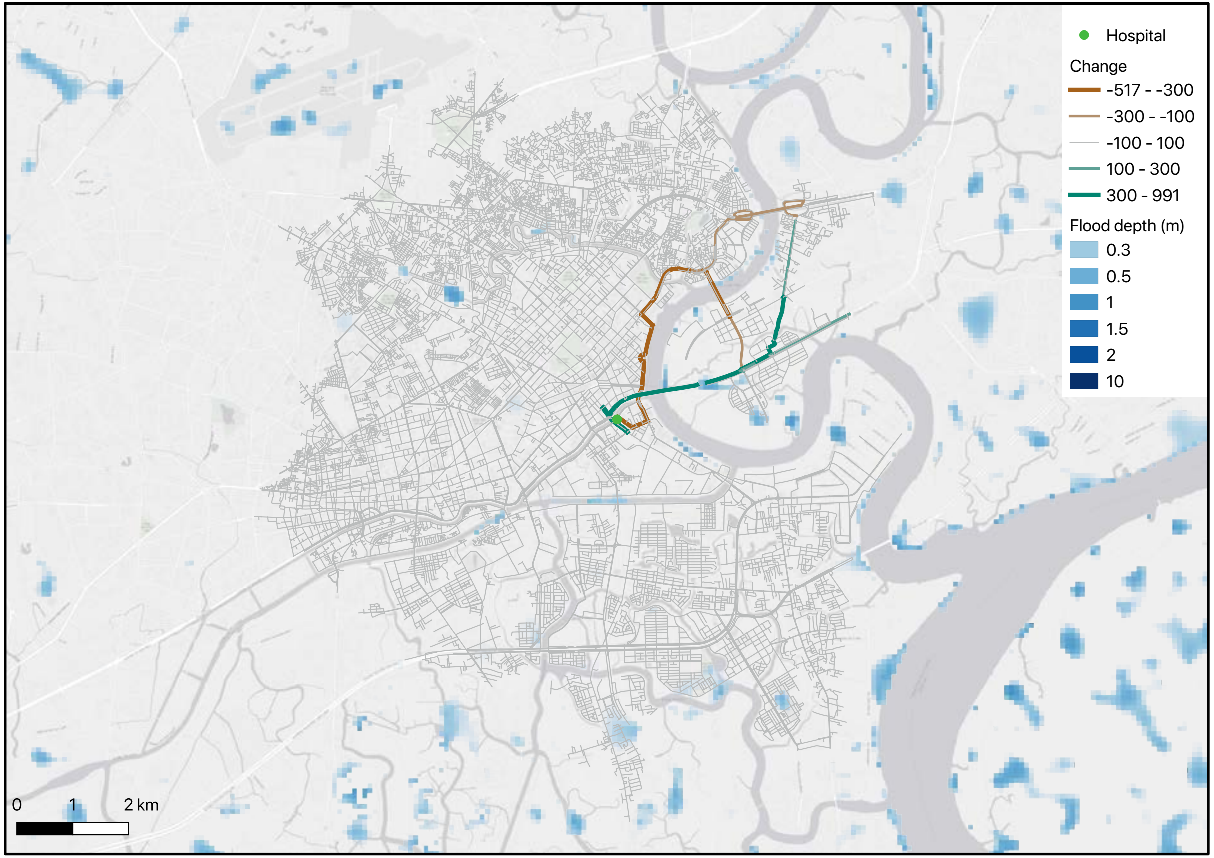


# Road criticality in the 10-min catchment network of District 4 Hospital

(disrupted by pluvial flooding with 20-yr return period)



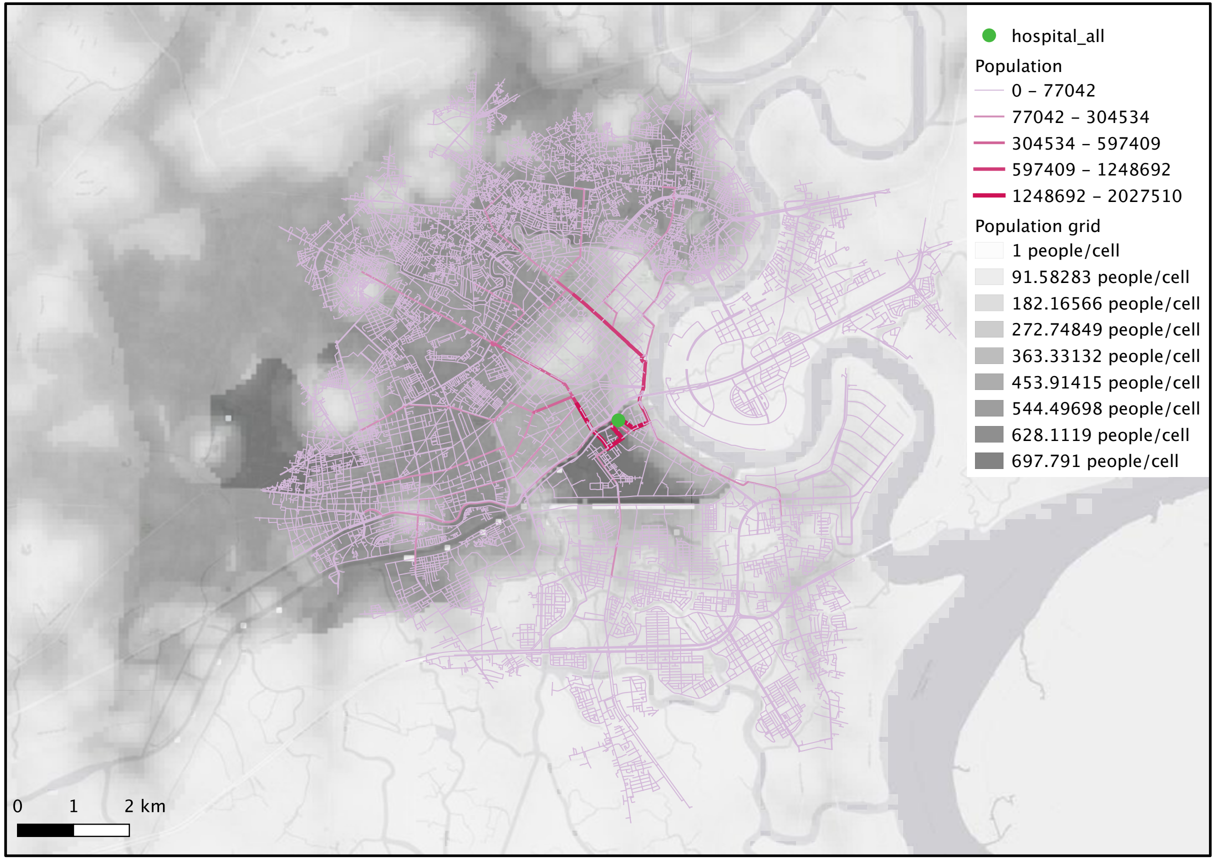
# Change of the edge betweenness centrality of road segments






(FRS) FUTURE RESILIENT SYSTEMS

# Population density weighted OD-based edge betweenness centrality



# Summary

Figure: Singapore Mass Rapid Transit trains travel along lines at the Jurong East interchange in Singapore by Roslan Rahman/AFP/Getty Images

- **Both “economic” and ”societal”:** improve understanding of critical infrastructure and factors which may determine criticality
- **A “System-of-Systems” perspective:** the framework needs to consider the complete range of hazards and complex failure modes as a result of inter-related, upstream dependencies
- **The favourable investment in resilience:** undertake further economic and engineering research to better understand and quantify a suitable level of investment in technical resilience

Dr Yi Wang
yi.wang@sec.ethz.ch

29 July 2021

frs.ethz.ch

CREATE ETH zürich

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE NUS National University of Singapore STEVENS INSTITUTE of TECHNOLOGY THE INNOVATION UNIVERSITY ILLINOIS

(FRS) FUTURE RESILIENT SYSTEMS